21 Greenhouse Gas Emission Reduction Using Advanced Heat Integration Techniques

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Abstract: Consuming about 20% of total energy annually in the USA (according to DOE in 1994), the chemical industry is a major source of greenhouse gas (GHG) emissions. It has been widely recognized that a significant reduction of energy consumption and GHG emissions in chemical processes must implement advanced heat integration technologies in a holistic way.

Heat integration is a family of technologies for improving energy efficiency. The technologies can be applied to the design of heat exchanger networks, heat-integrated reaction-separation systems, etc. Pinch analysis is the foundation of heat integration. In this chapter, the applicability of pinch technology in GHG emission reduction is reviewed first. Furthermore, the concept of "total site," which is valuable for energy targeting and integration at regional level, is described. A "total site" includes not only traditional industrial processes, but also commercial and residential energy users into the scope.

Then more advanced concepts in heat integration are introduced. The concepts are developed based on the observation of problems arising in heat integration applications – stability of heat-integrated systems in operation. The known modeling work addressing these issues will be reviewed thoroughly. The basic principles on how the disturbance-propagation-rejection models for these major chemical processing systems can be adopted in process synthesis and analysis stages will be discussed.

The concept of "total site" has been further extended to greenhouse gas emission targeting and reduction. Carbon dioxide (CO_2) emission focused pinch analysis methodology is reviewed, which is valuable for obtaining the optimal energy resource mix of fossil fuel and renewable energy for the regional or national energy sector.

Introduction

The chemical industry is one of the largest energy-consuming sectors in the USA. According to the US DOE's analysis, this industry consumes approximately 20% of total industrial energy consumption (1994), and contributes in a similar proportion to the nation's greenhouse gas (GHG) emissions. There are great potentials to reduce the energy demand and GHG emissions in chemical process systems using advanced heat integration technologies. The basic heat integration methodology was developed in the past decades under the label "Pinch Analysis." Some key points have been published at the end of 1970, but it was Linnhoff and his coworkers [1] who developed the basis of pinch technology, which is now considered as the foundation of heat integration.

Pinch analysis was originally developed based on thermodynamic principles to identify the optimal energy recovery strategies between the matches of hot and cold streams. It provides tools that allow the users to investigate energy flows within a process and identify the most economical ways of maximizing heat recovery and of minimizing the demand for external utilities purchased elsewhere (e.g., steam and cooling water), thus contributing to GHG emission reduction. The core concept is to match the available internal heat sources (hot streams) with the appropriate heat sinks (cold streams) to maximize the energy recovery and minimize the cost of external heat sources. Some specialized software

packages for implementing the pinch point analysis are available, such as Super Target™ (KBC Energy Services), Aspen Pinch™, Hextran™ (Simsci), and Honeywell Exchangernet™. Taking the Super Target™ suite, for example, it allows the user to carry out an in-depth pinch analysis for the heat integration within processes, columns, and a large site, respectively, using the PROCESS, COLUMN, and SITE modules.

Over the past decades, pinch analysis has been successfully used to reduce energy consumption site-wide [2] and in individual processes. The applications of pinch analysis in industrial sectors such as oil refining, chemicals, pulp and paper, etc., can typically identify opportunities for 10–35% energy consumption savings [3]. Due to its powerful function, the application of pinch analysis is extended to many fields, such as wastewater treatment [4, 5], hydrogen integration [6, 7], emission targeting [8], and even financial management [9].

In this chapter, the fundamentals of pinch analysis are briefly introduced first. It will cover all of the following aspects: setting energy targets by the construction of composite curves, grid diagram for developing the heat exchanger network (HEN), plus/minus principles for process modifications, appropriate placement of units, principles of data extraction, mathematical programming approach, total site concept, etc. Then more advanced concepts about the controllability and operability issues of heat integration system are addressed. A disturbance propagation and control (DP&C) model is introduced to the HEN design approach to handle the disturbance issue. This will lead to the optimal design solution both in the criteria of economic cost and controllability. At last, a novel carbon emission pinch analysis (CEPA) methodology, which is developed from traditional pinch analysis, is introduced for emission reduction targeting and planning from industrial sites to regional or national energy sectors. It can identify the minimal usage of low-carbon emission yet high-cost energy resources, and obtain the optional energy resources allocation scheme.

The Basics of Pinch Analysis

Pinch analysis is a rigorous, structured approach for identifying the bottlenecks in industrial process energy use. The minimum theoretical utility requirement in a process (target) can be calculated for overall energy use, as well as for specific utilities (LP, HP steam, cooling water, etc.) ahead of any detailed heat integration system design activities. Pinch technology can be used to extend the analysis to the site-wide integration of a number of processes by means of utility systems. When considering any pinch-type problem, the same principles apply:

- A process can be defined in terms of supplies and demands (or sources and sinks) of energy.
- The optimal solution can be achieved by appropriately matching sources and sinks by following thermodynamic laws.
- The defining parameter in determining the suitability of matches is the temperature of streams.
- Inefficient transfer of resource can block identification of an optimal solution.

Energy Targets

Constructing the composite curves. The most fundamental concept in pinch analysis is the so-called composite curve. Composite curves are used to determine the minimum energy consumption target for a given process system. The curves are profiles of heat availability (demonstrated by the hot composite curve) and heat demands (shown by the cold composite curve). The degree to which the curves overlap is a measure of the potential for heat recovery, as illustrated in ➋ *Fig. 21.1*. The gray zone in ➋ *Fig. 21.1*, where two composite curves overlap (heat duty-wise), is the amount of heat that can be recovered through heat integration.

To construct the curves, it requires only a complete and consistent energy balance of the process. The data are used to define the process streams in terms of their temperatures, mass flow rates, as well as heat capacities and heating or cooling requirements. These data can be obtained from one or all of the following ways: plant measurements, design data, and simulation. Once identified, these process streams are then divided into sources and sinks.

A source is the stream that has a certain amount of heat to be removed, out of which a fraction or whole can be recovered. Such process streams are called hot streams. A sink corresponds to a stream that must be heated, which is called a cold stream. In pinch analysis, process streams should be identified and then divided into source and sink

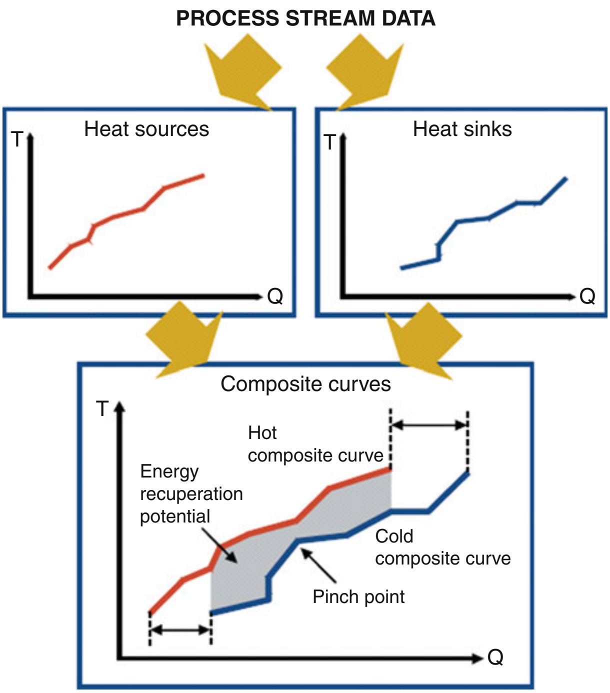

Fig. 21.1
The composite curves [3]

Table 21.1
Example data for building composite curves [3]

Stream	Stream type	Supply temperature (°C)	Target temperature (°C)	Heat duty (kW)	CP (kW/°C)
1	Hot	200	100	2,000	20
2	Hot	150	60	3,600	40
3	Cold	80	120	3,200	80
4	Cold	50	220	2,550	15

streams. This step is called data extraction, which is crucial for any pinch analysis. The following example explains how to do the data extraction.

Table 21.1 presents the stream data chosen to illustrate the construction of the composite curves. The following elements are necessary:

- Stream or segment temperatures: the supply temperature T_s and the target temperature T_t
- Heat capacity flow rate of each stream or segment, defined as $CP = \frac{\Delta H}{\Delta T}$

where ΔH is the enthalpy variation over the temperature interval ΔT, and *CP* is defined as mass flow rate (kg/s) × heat capacity (KJ/(°C·kg)) and has a unit of kW/°C. For example, stream 2 is cooled from 150°C to 60°C, releasing 3,600 kW of heat. Its *CP* value is 40 kW/°C.

Figure 21.2a shows the hot streams plotted individually on a temperature-duty (or temperature-enthalpy) diagram. The slope of composite curve is the inverse of the CP value. By adding the enthalpy changes of the individual streams within each temperature interval, the hot composite cure is constructed as shown in *Fig. 21.2b*. Note that in *Fig. 21.2b*, from 150°C to 100°C, the slope of the composite curve in this section is reduced. In a similar way, the cold composite curve can be constructed, as illustrated in *Fig. 21.2c* and *d*.

Determining the energy targets. An important part of pinch analysis is the Minimum Energy Requirement (MER) for a given process or plant. This information is used to identify the maximal potential for improvement before starting the detailed process design. To determine the minimum energy target of a process, the cold composite curve is moved left horizontally toward the hot composite curve, as shown in *Fig. 21.3a*. Please note that the enthalpy axis measures relative quantities and it only represents the enthalpy change of process streams. Moving a composite curve horizontally does not, in any way, change the stream data. The relative position of the composite curves depends on the minimum allowable temperature difference, ΔT_{min}, which is the minimum temperature difference that is allowed in a heat exchanger (note that the value of ΔT_{min} is usually given before design based on engineering experience; optimal determination of its value is a complicated problem). This also determines the pinch position where the heat transfer between the hot and cold streams is the most constrained. A value of 10°C is used in this example.

In ➋ *Fig. 21.3b*, the overlap between the composite curves is the maximum heat recoverable between the hot and cold streams in the process; the remaining heating and cooling needs are the minimum hot utility requirement (Q_{Hmin}) and the minimum cold utility requirement (Q_{Cmin}) of the process, respectively, for the chosen ΔT_{min}. In this

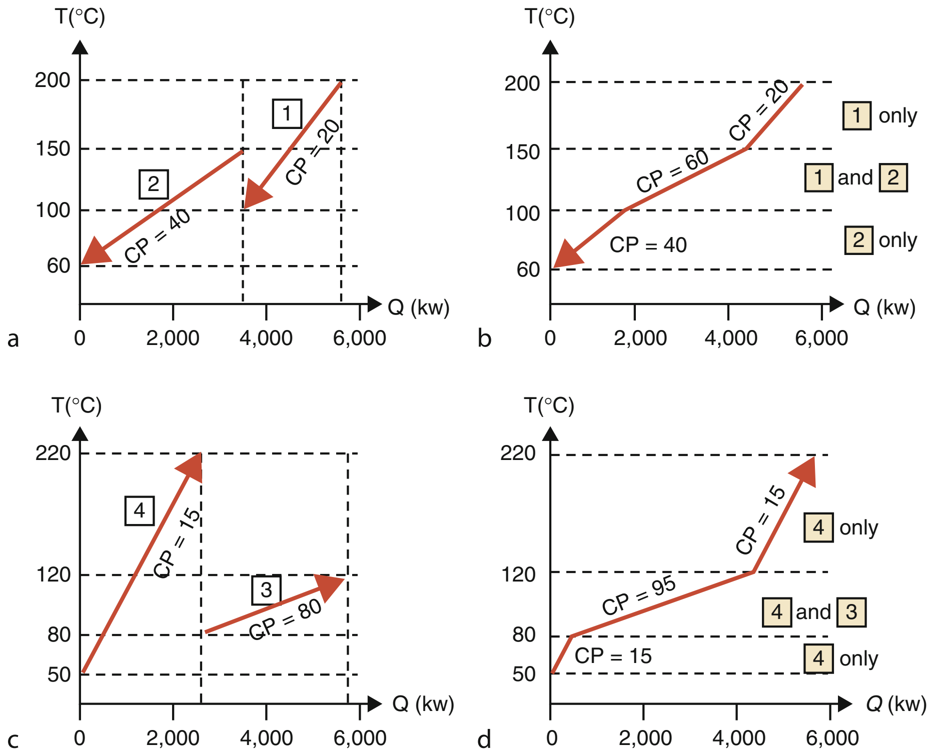

Fig. 21.2
Constructions of composite curves [3]

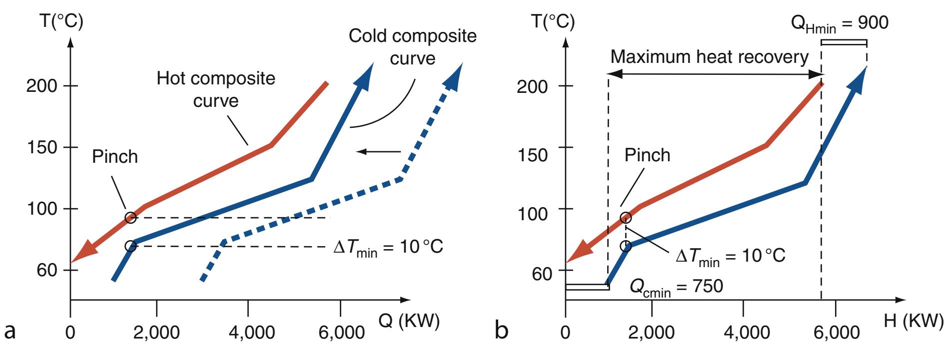

Fig. 21.3
Determine the energy targets by using the composite curves [3]

example, the minimum hot utility requirement ($Q_{H\text{min}}$) is 900 kW and the minimum cold utility requirement ($Q_{C\text{min}}$) is 750 kW, respectively, as indicated in *Fig. 21.3b*.

As demonstrated in the above example, pinch analysis enables the setting of targets for minimum energy consumption prior to any detailed heat exchanger network (HEN) design and allows to quickly indentify the scope of energy savings at an early stage of synthesis.

The point of the closest approach between the two composite curves, where ΔT_{min} is reached, is known as the pinch point. The pinch point is determined by the minimum temperature difference that will be accepted in any heat transfer unit. The pinch principle states that any design where heat is transferred across the pinch will require more energy than the minimum requirement. Consequently, the pinch point divides the problem into two independent subsystems, that is, the hot-end subsystem and the cold-end subsystem.

In principle, the region above the pinch only requires hot utility, while the region below the pinch only requires cooling utility (see *Fig. 21.4*). According to pinch design rules, no heat should be transferred from the hot-end subsystem to the cold-end subsystem. For example, if α amount of cross-pinch heat is transferred from the subsystem above the pinch to that below the pinch, then this cross-pinch heat needs to be supplied by an equivalent amount of hot utility above the pinch plus the same amount of cold utility below the pinch. Needless to say, this situation should be avoided in any case.

Selection of ΔT_{min}. Generally, saving energy may increase the capital cost, and thus often there is a need of trade-off between capital and energy costs. This can be demonstrated by examining the composite curves. As the separation between hot and cold composite curves (ΔT_{min}) increases, the overlap between the hot and cold streams becomes reduced, thereby decreasing opportunities for heat recovery, and in turn increasing the utility cost (*Fig. 21.5*). Meanwhile, if ΔT_{min} is increased, which means the permissible minimum

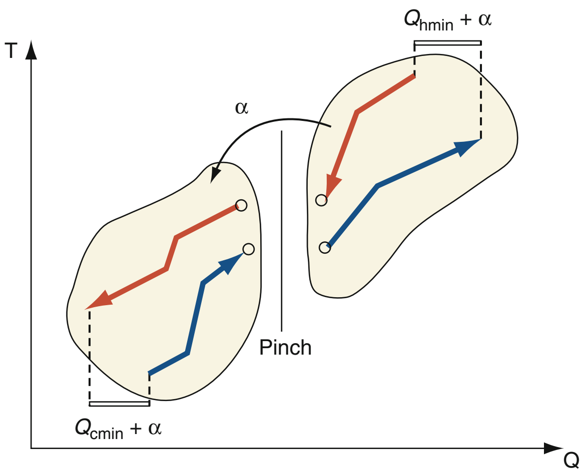

Fig. 21.4
Heat transfer across the pinch point [3]

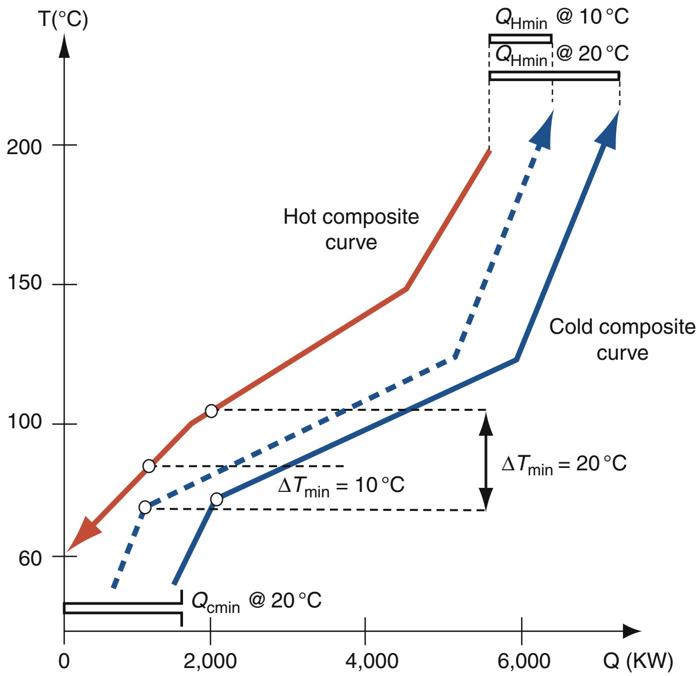

Fig. 21.5
Effect of ΔT_{min} [3]

temperature driving force between the hot and cold streams is increased, this will allow a greater temperature difference in any heat exchanger. Then, heat exchangers would be smaller in size, thereby making the capital cost for individual heat exchanger lower. Thus, the higher energy cost may be offset by the reduced capital cost of heat exchangers.

Figure 21.6 shows a generalized trend of energy cost and capital cost when ΔT_{min} changes. It is very obvious that for any given plant, there exists an optimum value of ΔT_{min} which can minimize the total cost of energy and capital. If the cost of energy and the cost of heat exchangers are known for a given plant, it is possible to predict the optimum value of ΔT_{min} ahead of detailed design. In practice, ΔT_{min} for a particular process is often selected by the two factors: the shape of composite curves and the engineer's experience. For chemical processes, and where utilities are used for heat transfer, ΔT_{min} values are typically in the range of 10–20°C. For low temperature process using refrigeration, a lower ΔT_{min} value, for example, 3–5°C, could be used to minimize expensive power demands in a refrigeration system.

Targeting for multiple utilities: the grand composite curve. Most processes are heated and cooled using several different utility levels (e.g., different steam pressure levels, furnace flue gas, cold water, refrigeration levels, etc.). It is desirable to increase the use of cheap utility levels and decrease the use of expensive utility levels. For example, using low-pressure (LP) steam instead of high-pressure (HP) steam, and cooling water instead of refrigeration can reduce the energy cost.

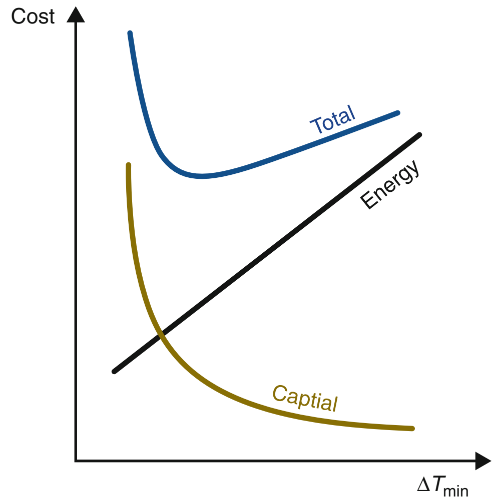

Fig. 21.6
Energy/capital trade-off [3]

Composite curves can provide the overall energy targets. However, they do not clearly indicate the exact amount of energy needed to supply by various utility levels. The grand composite curve, which plots process energy deficit (above the pinch) and energy surplus (below the pinch) as a function of temperature, can handle this problem and determine the multiple utilities targets.

To construct the grand composite curve, a small mathematical adjustment must be made to the composite curves. The hot composite curve is shifted down and the cold composite curve is shifted up separately by 1/2 ΔT_{min} each, until they touch at the pinch point. The resulting composite curves are referred as the shifted curves, and have no real physical meaning. They are merely a step in the construction procedure, which ensures that the resulting grand composite curve shows the required zero heat flow at the pinch point.

The grand composite curve is generated by plotting the heat load difference between the hot and cold composite curves as a function of temperature (*Fig. 21.7*). It provides a graphical representation of the heat flow through the process, from the hot utility to those parts of process above the pinch point, and from the process below the pinch point to the cold utility. The pinch point is where the curve intercepts the temperature axis (*Fig. 21.7*).

Figure 21.8a shows a grand composite curve where high-pressure (HP) stream is used for heating, and refrigeration is used for the cooling process. In order to reduce the utility costs, some intermediate utilities, such as medium-pressure (MP) steam, low-pressure (LP) steam, and cooling water (CW), can be used as an alternative. *Figure 21.8b* shows targets for these alternative utilities.

The target for LP steam is determined by plotting a horizontal line at the LP steam temperature from the T-axis until it intercepts the grand composite curve. The MP steam

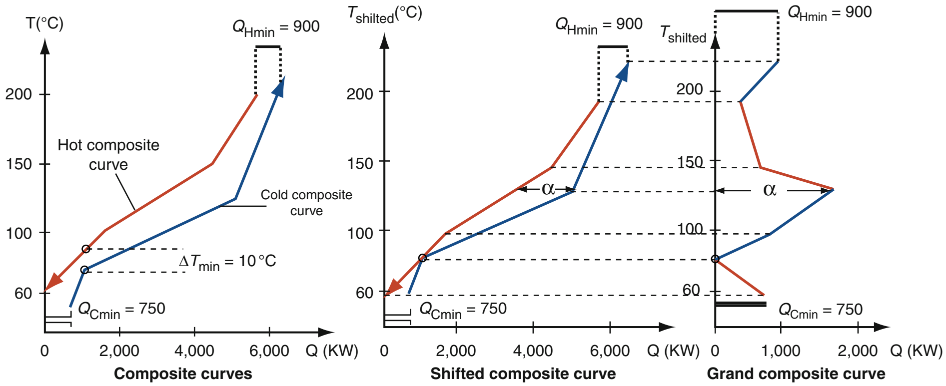

Fig. 21.7

Construction of the grand composite curve [3]

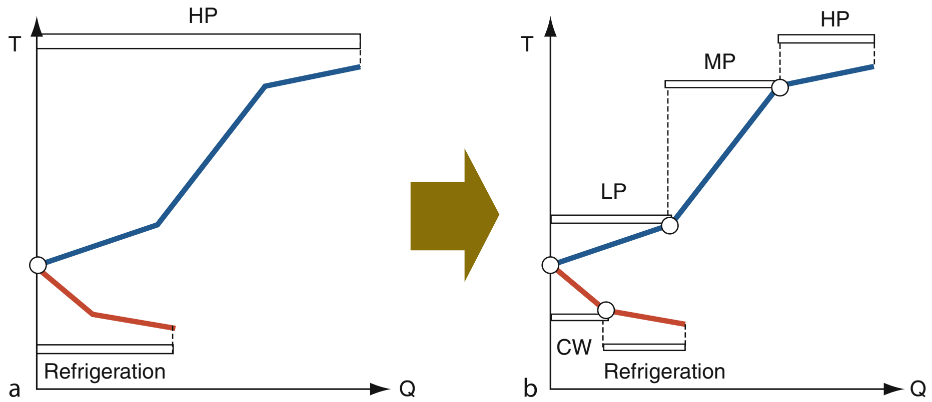

Fig. 21.8

The grand composite curve for multiple utilities targeting: (a) before targeting; (b) after targeting [3]

target can be obtained in a similar way. The remaining heating duty is satisfied by HP steam. A similar procedure can be done below the pinch to determine the use of cooling water instead of refrigeration. In summary, the grand composite curve is one of the basic tools used in pinch analysis for the selection of appropriate utility levels and for targeting optimal heat loads of various utility levels to minimize the total utility cost.

Heat Exchanger Network Design

The targeting step in a pinch analysis includes targeting for minimal energy usage, targeting for process modifications, targeting for multiple utilities, and appropriate placement of heat engines and heat pumps. The aim of targeting step is to explore various

process improvement options, such as energy recovery, process modification, and utility system integration, quickly and easily without going into the detail of heat integration design. The key improvement options identified in the targeting stage need to be realized in the detailed design. The heat exchanger network (HEN) design procedure which is based on pinch principle can translate the idea of improvement option into specific detailed design. This design procedure uses the so-called grid diagram to represent the heat exchanger networks. This method will systematically lead the designer to good network design schemes that achieve the energy targets within practical limits.

Grid Diagram. Figure 21.9 illustrates a grid diagram, which is a working frame for synthesizing a heat exchanger network (HEN). The hot streams run from left to right at the top, while the cold streams run in the opposite direction at the bottom, as illustrated in Fig. 21.9. The vertical line with two arrows connecting the hot stream with cold stream represents the heat exchanger between process streams. Heaters on cold steams and coolers on hot streams are shown with circles. The process pinch location is represented by a dashed line dividing the grid diagram into two parts. The pinch hot and cold temperatures obtained from composite curves by the determined $\Delta T_{\min}$ are shown at the top and bottom of the dashed line. The process above the pinch (heat sink) is on the left side of the dashed pinch line and the process below the pinch (heat source) is on the right side. Overall, in the grid diagram, the temperatures of streams decrease from the left side (above the pinch) to the right side (below the pinch).

According to the pinch principles discussed before, the process is divided into two independent subsystems at the pinch point and any heat transfer across the pinch will require more energy than the minimum requirement. Thus, the HEN design should be conducted in two steps, above the pinch and below the pinch, respectively. The design

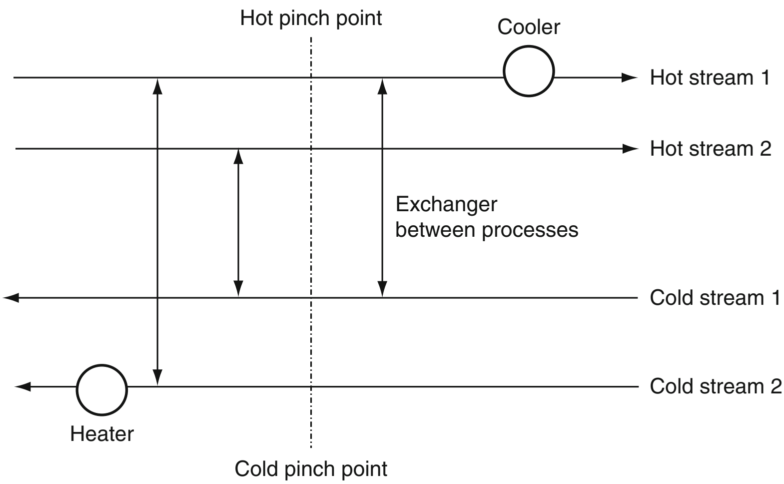

Fig. 21.9
Grid diagram for developing the heat exchanger network

starts at the pinch, where the heat transfer is most constrained. To determine the match of steams sequentially, heuristic feasibility rules could be used. Note that stream matching can be also determined by rigorous mathematical programming methods [10–14].

For a pinch match above the pinch (at the left side), the following heuristic rule can be followed, that is, $CP_{\text{hot}} \leq CP_{\text{cold}}$. In this context, *CP* means mass flow rate × specific heat capacity. This rule can be easily understood by the fact that only hot utility is needed above the pinch, so the *CP* value of the cold streams must be greater than the *CP* value of the hot streams.

Similarly, below the pinch (at the right side), for each pinch match, the following heuristic rule holds: $CP_{\text{hot}} \geq CP_{\text{cold}}$. The two rules above can be summarized as $CP_{\text{in}} \leq CP_{\text{out}}$. It means for a match at the pinch, the *CP* value of the stream going out of the pinch must be greater than the *CP* value of the stream coming into the pinch. For example, when consider the process above the pinch, the *CP* of hot stream, which is coming into the pinch, is smaller than the *CP* of cold stream, which is going out of the pinch.

Number of matches, paths, and loops. Linnhoff and coworkers [1] pointed out that the minimum number of units (matches) N_E needed to recover the energy between N_s process streams using N_u utilities can be expressed by the following equation, if the synthesis problem cannot be feasibly divided into two or more energy-independent problems:

$$N_E = N_s + N_u - 1$$

If there are N_{loop} loops present in the network, this equation can be modified as:

$$N_E = N_s + N_u - 1 + N_{\text{loop}}$$

The concept of path means a physical connection through streams and heat exchangers for the transfer of energy between utilities. A path allows the modification of the temperature difference between hot and cold streams. Loop is a closed trajectory connecting several heat exchangers. These two concepts are very useful in the optimization of heat exchanger network design.

Reducing the HEN. The HEN design for minimum energy requirements based on the pinch principle ensures the maximal energy recovery, thus minimizing the energy cost. However, this design may increase the number of units needed, and thus demanding a high equipment cost. In this case, merging some units and reducing the number of equipments may contribute more significantly to the total cost saving through trade-off between the capital and operating costs. The final optimization of the design will depend on the cost of energy and equipment in the particular case analysis. As a rule of thumb, breaking the loop including the heat exchanger with the smallest load and removing this unit in a loop can greatly reduce the total cost of the design. The loss of energy recovery capacity due to the reduction of small units can be partly compensated by increasing the heat transfer area of large units. This can be explained by the fact that for small heat exchangers, the fixed capital cost of equipment, which includes installation, instrumentation, control, supervising, and maintenance costs, is usually larger than the cost of incremental heat transfer area.

Appropriate Placement and Process Modifications

Appropriate placement of units. The appropriate placement principle determines the optimal location of individual units against the pinch. It applies to heat engines, heat pumps, distillation columns, evaporators, furnaces, and any other operating units which can be represented in terms of heat sources and sinks.

In the process industry, the use of combined heat and power systems has been increased significantly. In such cogeneration units, the heat rejected by a heat engine, such as steam turbine, gas turbine, or diesel engine, is used as hot utility and integrated into the process. If a heat engine is integrated across the pinch, as shown in *Fig. 21.10a*, the process will still require the same amount of utilities (Q_{Hmin}). When the heat engine is completely integrated above the pinch as shown in *Fig. 21.10b*, the heat is rejected to the heat sink region of the process, thus exploiting temperature differences between the utility and process, and producing work at a very high efficiency. After integration, the import of W amount of extra energy from heat sources can produce W amount of shaftwork and the efficiency of heat to work conversion appears close to 100%. A similar situation will arise when heat engine is completely integrated below the pinch.

Heat pumps, such as vapor compression and refrigeration, are systems that absorb heat at a low temperature in an evaporator, consume shaftwork to compress the working fluid, and reject heat at a higher temperature in a condenser. If the pump is located completely above the pinch, it simply transforms power into heat, which is not economical. If it is placed completely below the pinch, the situation is even worse because work is

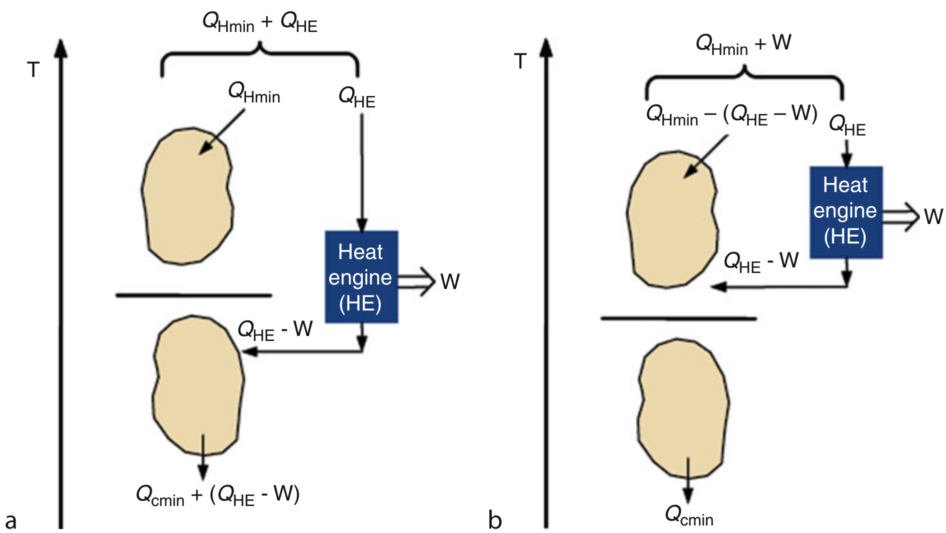

Fig. 21.10
Integration of heat engine exhaust: (a) across the pinch; (b) above the pinch [3]

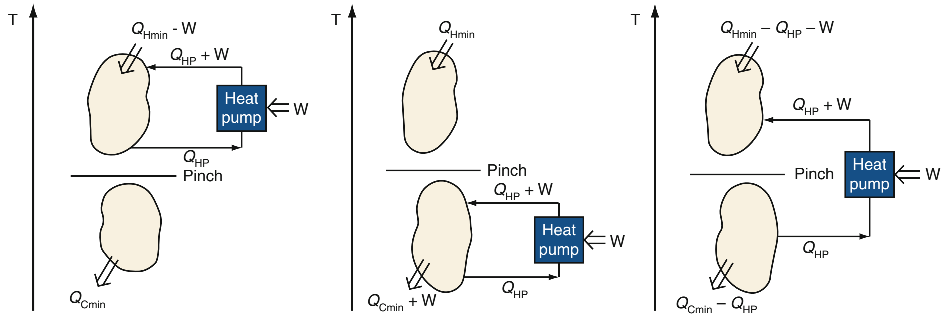

Fig. 21.11

Integration of a heat pump above, below, and across the process pinch [3]

transformed into waste heat. The only appropriate way to place a heat pump is across the pinch, where heat is absorbed below the pinch and rejected above the pinch, as shown in *Fig. 21.11*.

In fact, the principles introduced above can be concluded as the Townsend and Linnhoff heuristics [15]:

1. When positioning heat engines to reduce the total utilities, place them entirely above or below the pinch.
2. When positioning heat pumps to reduce the total utilities, place them across the pinch.

Plus/minus principle in process modifications. For a process, the heat and material balance determines the shape of the composite curves and then the minimum energy requirements set by the curves. By changing the heat and material balance, the composite curves would change accordingly. Thus, it is possible to further reduce the energy requirement of the process. There are several parameters that could be changed, such as distillation column operating pressures and reflux ratios, feed vaporization pressures, etc. There are so many choices that a guide is needed to confidently predict the parameters that could be changed to reduce the energy consumption. By applying the thermodynamic rules based on pinch analysis, which is called the "plus/minus principle," it is possible to identify the appropriate process modifications that will improve the energy recovery significantly. In general, the hot utility can be reduced by (1) increasing hot stream (heat source) duty above the pinch and (2) decreasing cold stream (heat sink) duty above the pinch. Similarly, the cold utility target can be reduced by (1) decreasing hot stream duty below the pinch and (2) increasing cold stream duty below the pinch. This is termed as the plus/minus principle for process modifications. This simple principle provides a reference for any adjustment in process heat duties, such as vaporization of a recycle, etc., and indicates which modifications would be beneficial and which would be detrimental.

Often, it is possible to change temperatures rather than heat duties. It is clear from the composite curves that temperature changes confined to one side of the pinch will not have any effect on the energy targets. However, temperature changes across the pinch can change the

energy targets for the process. For example, reducing the feed vaporization pressure (cold stream) may move the feed vaporization duty from above the pinch (minus) to below the pinch (plus). Hence, a reduction of vaporization duty is achieved in both hot and cold utilities. This can be considered as an application of plus/minus principle twice.

When a cold stream is removed from the region above the pinch and placed below the pinch, certainly, the shape of cold stream composite curve will change accordingly. The hot utility needed will diminish by the exact amount of cold utility moved. Similarly, moving a hot stream from the region below the pinch to above the pinch will reduce the hot utility consumption. In general, the above observations for beneficially shifting process temperatures can be summarized as follows: (1) shift hot streams from below the pinch to above, and (2) shift cold streams from above the pinch to below.

Modifications of distillation column. Distillation column unit is the basic processing step in many chemical plants. Although distillation is highly energy-intensive, consuming energy in the magnitude of several MJ/s, it has a low thermodynamic efficiency (less than 10% for a difficult separation). Thus, it is one of the important areas for heat integration. During the retrofit or new column design, pinch analysis can be exploited to identify the targets for appropriate column modifications in order to reduce utilities cost and to improve energy efficiency. Some software packages, such as Super Target™ (KBC Energy Services), Aspen Pinch™, provide advanced software tools for the implementation of column targeting and modifications.

➋ *Figure 21.12* shows an example of the column grand composite curve (CGCC) [17], a tool that is used for column pinch analysis. CGCC is based on the concept of minimum thermodynamic condition for a distillation column, which pertains to thermodynamically reversible column operation. In this ideal condition, a distillation column would operate at minimum reflux, with an infinite number of stages, and with side reboilers and side condensers placed at each stage with appropriate heat loads for the operating and equilibrium

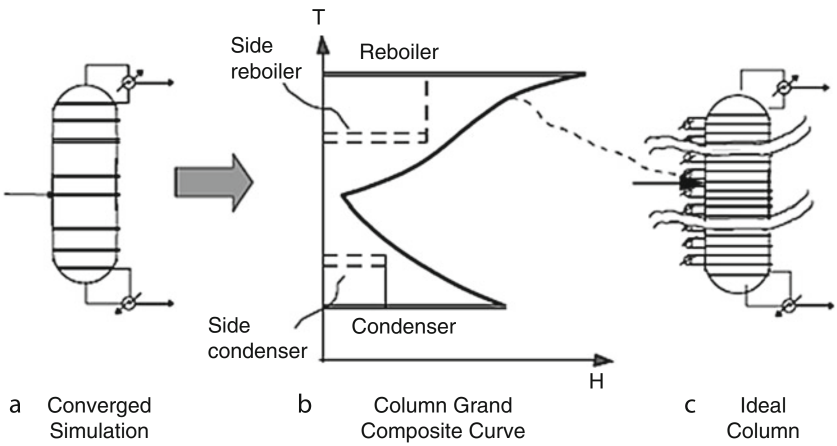

Fig. 21.12
Column grand composite curve [16]

lines to coincide, as shown in ➋ *Fig. 21.12c*. In other words, the reboiling and condensing loads are distributed over the whole column. The stage-enthalpy (Stage-H) or temperature-enthalpy (T-H) profiles for such an ideal column therefore can represent the theoretical minimum heating and cooling requirements of the column operation. These profiles are termed as the column grand composite curves (CGCC).

Most industrial columns have certain inevitable losses or inefficiencies. In order to set realistic targets for the column modifications, these losses must be allowed. To handle this problem, Dhole and Linnhoff [17] developed a practical near-minimum thermodynamic condition (PNMTC) approach, which is adopted by many software. This approach takes into account the losses or inefficiencies introduced through practicalities of column design, such as pressure drop, multiple side products, side strippers, sharp separations, etc. The procedure for constructing the CGCC starts from a converged column simulation. From the simulation, the necessary column information is extracted on a stage-wise basis. Then the equations for equilibrium and operating lines are solved simultaneously at each stage for designated light-key and heavy-key components. The enthalpy deficits used in plotting the CGCC are calculated at each stage. At last, these enthalpy deficits are cascaded to construct the CGCC either in Stage-H or T-H dimensions.

Like the grand composite curve for a process, the CGCC provides a thermal profile for the column and can be used for identifying the targets for potential column modifications, such as feed location, reflux ratio, feed conditioning (preheating or precooling), and side condensing or reboiling. Based on the inspection of the CGCCs, the following order of implementation of different column modifications is recommended as shown in ➋ *Fig. 21.13*: feed location (appropriate placement), reflux ratio modification (reflux ratio vs. no. of stages), feed conditioning (preheating or precooling), and side condensing or boiling.

Feed location need to be carried out first since it may strongly interact with other column modifications. The feed enthalpy strongly influences the shape of CGCC near the feed stage. And the CGCC usually shows a pinch point near the feed stage. Inspection of the CGCC can identify any distortions due to inappropriate feed location. Normally, this kind of distortions will be apparent since the stage-H CGCC will have significant projections at the feed location (pinch point). This is due to a need for extra local reflux to compensate for the inappropriate feed location. The optimal feed stage can be obtained by trying alternate feed locations and observing its influence on the reflux ratio. When the feed is introduced too high up in the column, there will be a sharp enthalpy change on the condenser side of the stage-H CGCC and the feed should be moved down. Similarly, when the feed is introduced too low, there will be a sharp change on the reboiler side of the stage-H and the feed should be moved up. The optimal feed location not only removes the distortion in the stage-H CGCC but also reduces the condenser and reboiler duties.

Out of many other column modification options, the scope of reflux improvement must be considered first since it results in direct heat load savings at both reboiler and condenser. In ➋ *Fig. 21.13a*, the horizontal gap between vertical axis and T-H CGCC pinch point indicates the scope for reduction in heat duties through reduction of reflux ratio.

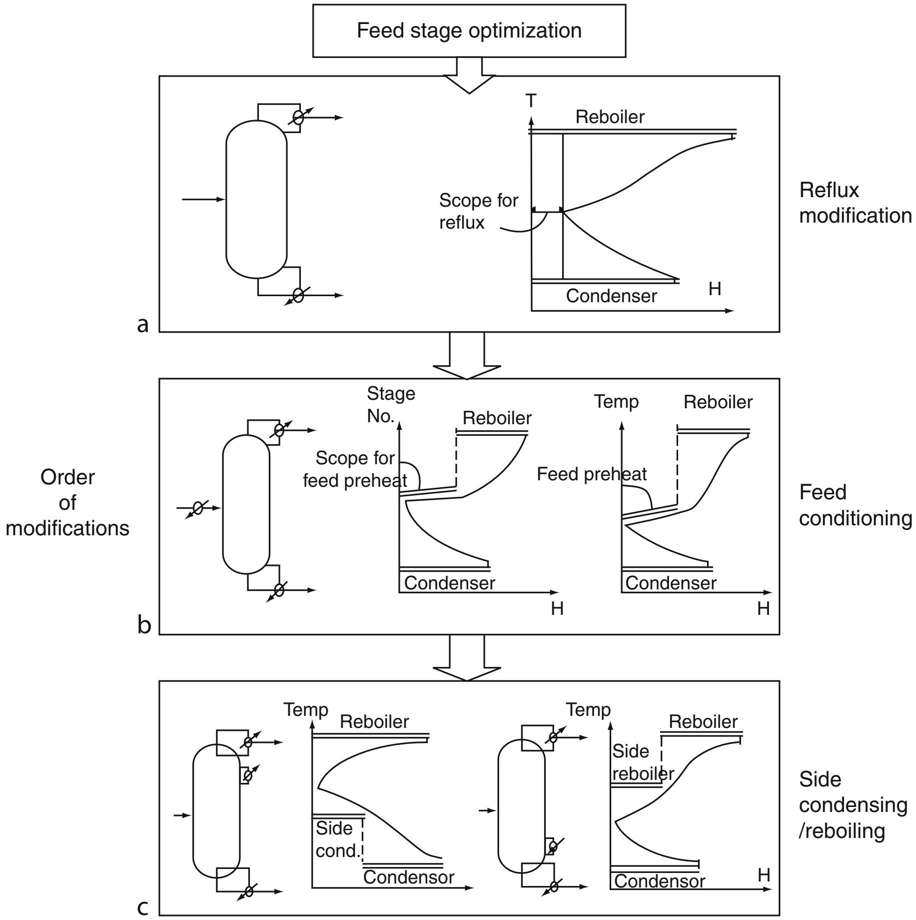

Fig. 21.13
Using column grand composite curve to identify column modifications [16]

When the reflux ratio is reduced (while increasing the number of stages to maintain the separation), the gap will decrease and the CGCC will move closer to the vertical axis, thus reducing the condenser and reboiler duties. It must be noted that when the reflux ratio is reduced, the number of stages will increase to maintain the desired separation. Thus, to obtain an optimal reflux ratio, the increase in the capital cost due to the increase of stages should be traded off against the savings in the operating cost due to reduced condenser and reboiler loads.

Inappropriate feed condition usually results a sharp enthalpy change in the CGCCs near the feed location and increases the heat load of condenser or reboiler. The scope of feed conditioning can be identified from the sharp enthalpy changes on the stage-H or T-H CGCCs. *Figure 21.13b* shows an example that the feed need to be preheated. The extent of the sharp enthalpy change on the CGCCs determines the appropriate preheating duty needed. Feed preheating not only reduces the reboiler duty but also

reduces the temperature levels at which the hot utility (for the reboiler and the feed preheater) needs to be supplied. For feed precooling, the situation is similar. Changes in the heat duty of feed preheaters or precoolers will lead to similar duty changes in the reboiler or condenser loads.

After the modification of feed conditioning, side condensing/reboiling should be analyzed. An appropriate side reboiler, like the feed preheaters, not only reduces the heat loads of column reboiler but also reduces the temperature levels at which the hot utility (for the main reboiler and the side reboiler) needs to be supplied. In *Fig. 21.13c*, the two CGCCs show the potential for side condensing and reboiling, respectively.

In general, feed conditioning is preferred to side reboiling or side condensing as it offers a more moderate and convenient temperature level. Meanwhile, the feed conditioning is external to the column and therefore easier to be implemented than side condensing/reboiling.

Till here, several ways of improving column thermal efficiency by stand-alone column modifications and their sequence are presented. In many cases, it is possible to further improve the overall energy efficiency of the process by appropriately integrating the column with the background process.

Figure 21.14 illustrates three examples of integrating the distillation column with the background process. The background process is represented by its grand composite curve.

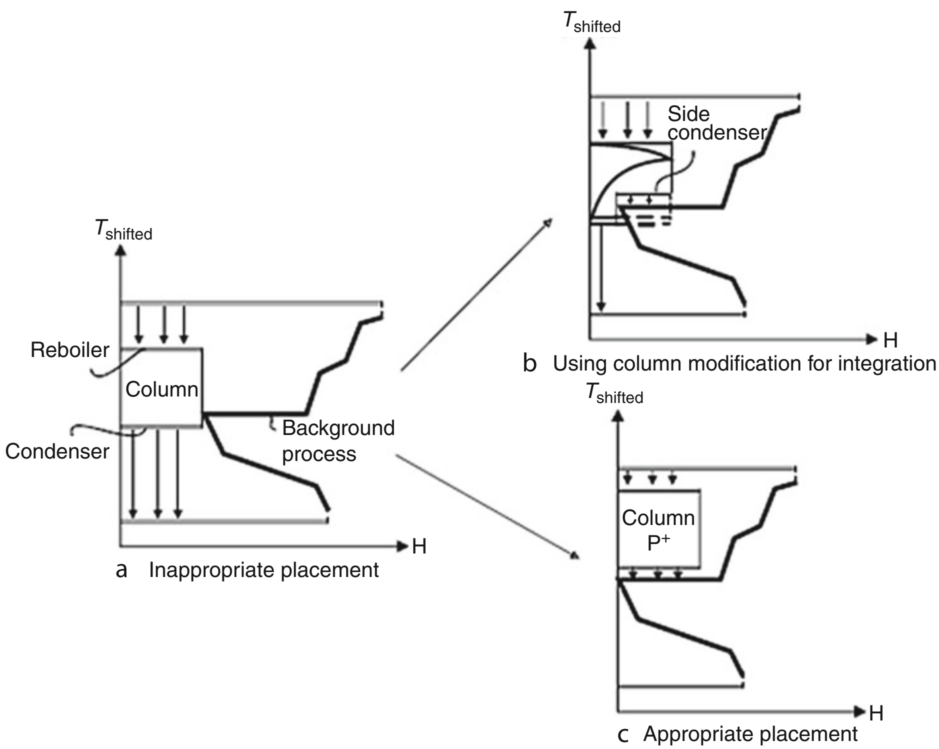

Fig. 21.14
Appropriate integration of a distillation column with the background process [16]

Figure 21.14a shows an example of an inappropriately placed column with its temperature range across the pinch temperature of the background process and without any potential for integration with the background process. *Figure 21.14b* illustrates a case that although the column temperature range still crosses the pinch temperature of the background process, a side condenser can be added to further improve the overall thermal efficiency as identified by the CGCC.

Figure 21.14c presents a different alternative integration scheme, which allows a complete integration between the column and the background process. In this scheme, the column pressure is increased to move the CGCC to one side of the process pinch point instead of crossing the pinch. Thus, the overall energy consumption of this scheme is just the energy consumption of the background process.

Although appropriate column integration can provide significant energy benefits, these benefits must be considered together with the relevant issues, like the associated capital investment and difficulties in operation.

Data Extraction

Before the pinch analysis can be done, various process information is needed. Note that the amount of information available from plant measurement, data acquisition systems, and simulation models of a process can be very large, and most of the data may be of no relevance to the analysis. It is thus necessary to identify and extract only the information that truly captures the relevant sources and sinks, and their interactions with the overall process. The required data involves process stream heating and cooling information, utility stream information, cost information, and some background information regarding the processes. In summary, the following data need to be collected for each process stream: mass flow rate (kg/s), specific heat capacity (kJ/kg·°C), supply and target temperature (°C), and heat related to a phase change (kJ/kg). Additionally, for the utilities and the existing heat exchangers, the following information needs to be acquired: existing heat exchanger area (m^2), heat transfer coefficient of heat exchangers ($kW/(m^2 \cdot °C)$), and utilities available in the process (water temperature, steam pressure levels, etc.).

Data extraction could be time-consuming and must be performed carefully as the results of pinch analysis strongly depend on this step. Poor data extraction can easily lead to missed opportunities for the process improvement. In extreme cases, poor data extraction can falsely show that the existing process design is already the optimal one in energy efficiency. Data extraction needs to be conducted in an appropriate way, which only accepts the critical parts of the existing design that cannot be changed. A key objective of data extraction is to recognize the parts of process that can be further modified during the analysis (e.g., adding new heat exchangers, changing the process temperatures, etc.). If during the data extraction, all the features of existing design are considered as fixed, then there will clearly be no scope for improvement. If the extraction does not consider any features of the existing design, then the pinch analysis conducted later may overestimate the potential benefits.

At the beginning of a data extraction, it is recommended that all process streams be included. The constraints, such as distance between processes, operability, and control and safety issues, can be considered later on. The experienced specialists may include some constraints at the beginning of data extraction. This can speed up the overall analysis; however, lots of experience is required to ensure that potential possible heat integration opportunities are not excluded by adding these constraints earlier. Hence, data extraction requires lots of experience and there are many sector specifics for data extraction. Not all of them can be covered here; however, some important heuristic rules have been developed as guidelines over the past years.

Do not mix streams at different temperatures. In a process flow sheet, the streams at different temperatures cannot be directly mixed together, as such direct non-isothermal mixing acts as a direct contact heat exchanger. Such mixing may involve cross-pinch heat transfer, and therefore increase the overall external utility requirement. It should not become a fixed feature of the data extraction. For example, if the pinch is located at 70°C, then mixing a stream at 90°C with a stream at 50°C will create a cross-pinch heat transfer and increase the energy targets. To avoid this, if mixing must take place due to process reasons, then the isothermal mixing must be considered. The streams involved in mixing should be considered independently and extracted separately as being mixed at the same target temperature.

Do not carry over features of the existing solution. This rule is illustrated with the example whose process flow sheet is shown in *Fig. 21.15*. Based on the original data extraction generated from the process flow sheet in *Fig. 21.15*, a HEN design is conducted using pinch analysis. The original data extraction and corresponding HEN design are illustrated in *Fig. 21.16*. Because the HEN design from pinch analysis, consisting of one heater, one cooler, and two exchangers, is identical to the existing

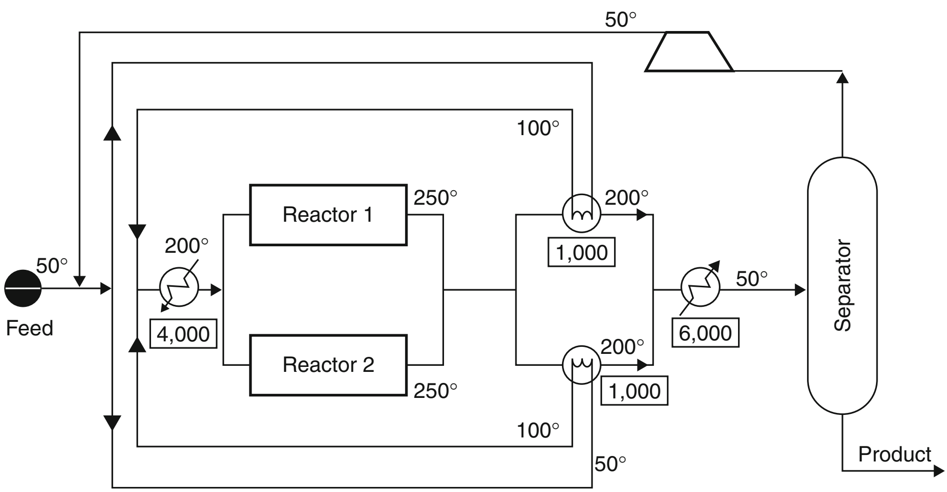

Fig. 21.15
Example process flow sheet for data extraction [16]

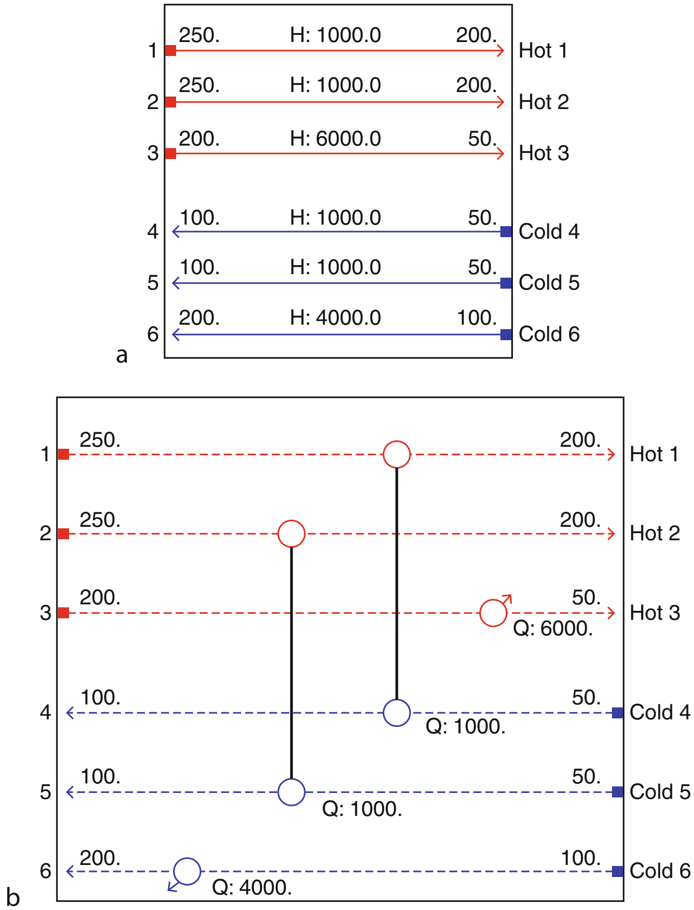

Fig. 21.16
Original data extraction and HEN design [16]

process flow sheet design in *Fig. 21.15*, it seems that the existing flow sheet design is already optimized and there is no opportunity for further improvement. The pinch analysis results no benefit.

However, the original flow sheet is not an optimal design and the original data extraction is not appropriate. *Figure 21.17* shows an appropriate method of data extraction from the existing process flow sheet and the corresponding HEN design. All the three cold streams previously extracted can be denoted as just one cold stream, and likewise only one hot stream needs to be extracted. The improved design is much simpler and easier to control. It shows significant additional potential for improved energy recovery, and reduces both the equipment cost and energy cost. The "appropriate" data extraction does not exclude any potential energy-saving opportunities. As this example illustrates, the practitioner should be careful in separating the relevant stream data from the original process flow sheet design and should not take over features from it.

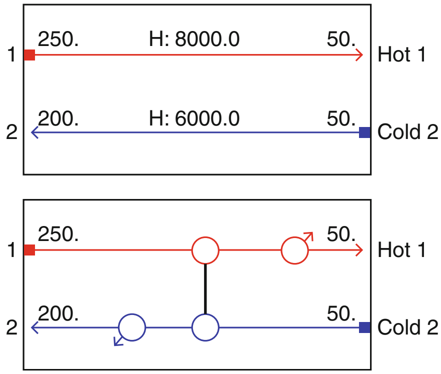

Fig. 21.17
Improved data extraction and HEN design [16]

Do not consider true utility streams. A true utility stream is a utility stream (steam, flue gas, cooling water, refrigerant, cooling water, etc.) that can be replaced in principle by any other stream (process or utility) for heat recovery. One of the goals of using pinch analysis is to reduce the usage of utilities. Therefore, if utility streams are extracted in a similar way to process streams, they will be considered as fixed features and thus no opportunities of reduction in utility use will be identified. However, in some cases, it is not practical to replace the utility streams by any other form of heat recovery. The utility streams are not true utility streams and need to be extracted as process streams. This is often the case for steam dryers, ejectors, and turbine drives. For example, when steam is required in a shift reactor to enhance the shift process, the steam is not a true utility. The steam is not just used for heating but is necessary for the reaction and cannot be replaced. In this situation, the steam must be extracted as a cold stream, to be heated and vaporized from the original feed condition to the appropriate steam temperature and pressure for the reaction.

Identify hard and soft constraints. A hard constraint would be a constraint that cannot be changed in any way, like the inlet temperature of a reactor, while a soft constraint is often open to change within certain range. An example of soft constraint is the discharged temperature of a product stream going to storage, which is often flexible within a range. It is sometimes possible to achieve more heat recovery by changing the soft constraints, such as temperature, pressure, and enthalpy conditions of streams, at the data extraction stage. So the soft constraints should be ideally extracted and the plus/minus principle for process modifications should be applied.

Total Site Concept

In the previous part, heat and power integration for a single process has been studied. Typically, industrial processes, such as refinery and petrochemical processes, operate as parts of large sites or factories. A total site is originally defined as an industrial system

consisting of several processes, whose material and energy needs are supplied by a central utility system. For example, in a large site where direct heat integration between processes (e.g., heat exchange between two streams from different processes) is difficult due to a long distance between them, indirect heat integration may be achieved through a utility system. By integrating a number of processes via the steam system, additional inter-process heat recovery can be achieved. Figure 21.18 shows a schematic of a typical process industry site involving several processes A, B, and C. These individually operated processes, some with their own utilities are served by a central utility system. The utility system consumes fuel, generates power, and supplies the necessary steam through several steam mains. There are both consumption and recovery of process steam via the steam mains between the different processes. Usually the individual production processes and the central services are controlled by different departments and operated independently. The site infrastructure therefore usually suffers from an inadequate overview design and control. For example, in a site involving 50 production processes, the grand composite curve of each individual process will suggest different steam levels. To minimize the total energy and capital cost of the whole site, it requires an approach to consider the individual process issues along with the site-wide utility planning together to identify the correct compromise in steam levels and loads.

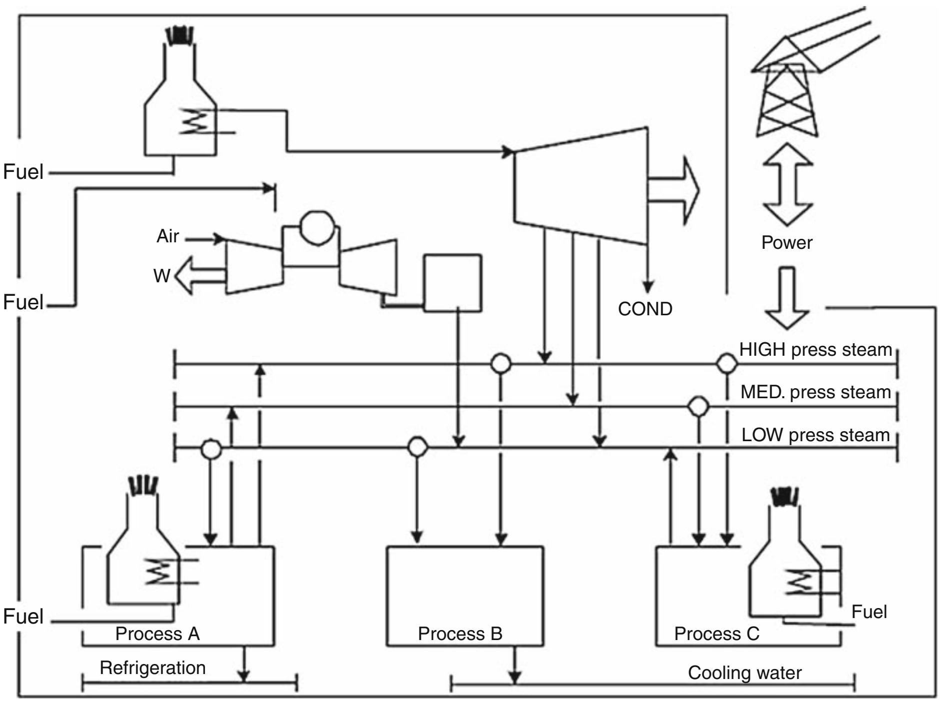

Fig. 21.18

Schematic of a site whose separately operated processes are linked indirectly through the utility system [3]

A graphical method, the so-called total site profiles, was first introduced by Dhole and Linnhoff in 1993 [8]. Klemes et al. [18] then extended this methodology to site-wide applications. This method allows a target to be set for the total site heat recovery. Site-wide analysis usually starts with a kick-off meeting to determine the detail levels each process should be studied and the scope of total site data extraction. In general, not all processes need to be analyzed at the same level. For example, some units may lack enough data for the analysis, and some processes do not need a detailed study due to their small size or low complexity.

Three models, black box, gray box, and white box, are used to represent the broad categories of detail level that may be applied to a process. Black-box processes are not to be studied in detail and only the overall utility consumption is considered. This may be because their energy consumption is very small, or heat recovery projects may be difficult to implement, or it is just not the right time for the company to invest in that area. So these processes are simply represented by their existing utility consumption profiles.

Gray-box processes only consider heat transfer that involves utilities. These processes usually have small scope of process–process heat exchange, but have significant utility use. In these cases, the process streams that are heated or cooled by utility are considered; however, the process–process heat exchange matches are not considered. In this way, the process/utility interface can be optimized in a site-wide area instead of internal optimization within the process. Again, there is no need to conduct individual pinch analyses for the processes.

White-box processes need to perform a detailed pinch analysis. These are usually complex processes with significant energy consumption. For these processes, grand composite curves are constructed. The source and sink profiles of these white-box processes, together with those of black-box processes and gray-box processes, are further modified to construct the site source sink profile (SSSP) which consists of a site heat source profile and a site sink profile. The construction procedure involves selecting parts of the grand composite curves that are satisfied by the central utility system and shifting the temperature. It is not the same as simply combining all the process stream data together into a single site data set, which would allow some far from realistic scenarios. Those scenarios do not consider the realistic constraints, such as distances, controllability, flexibility, etc., which will reduce the number of integration possibilities. For the detailed construction procedure, please see Ref. [16].

➲ *Figure 21.19* illustrates the construction site source sink profiles for a site consisting of four white-box processes (A, B, C, and D), and several other gray-box and black-box processes. In the total site profiles diagram, the site heat sources are shown on the left side and the site heat sinks are shown on the right side.

Total site analysis is used to determine the potential for maximizing indirect heat integration through central utilities. The analysis can identify the optimal balance of process steam generation via heat recovery and consumption, and also the optimum steam header pressures. After the site source profile and site heat sink profile are plotted, the composite curves of steam generation and consumption are also constructed. The heat should transfer from the heat source profile to the steam generation profile to generate steams. And also the heat from the steam usage profile should transfer to the

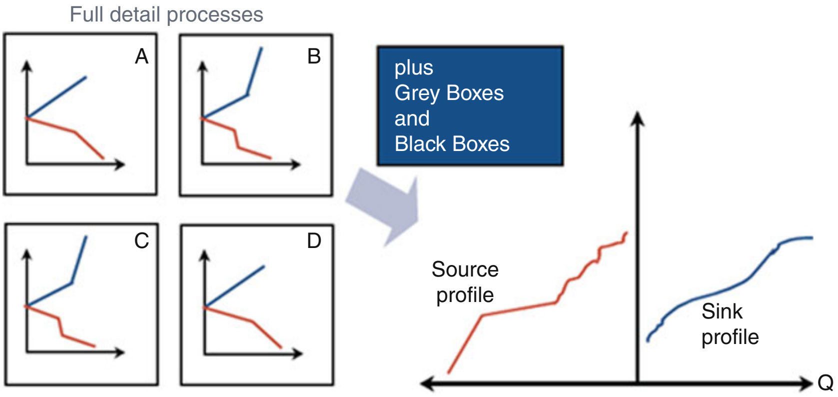

Fig. 21.19
Construction of the site-wide source sink profiles [3]

heat sink profile by the consumption of steam. By superimposing the current utility balance onto the site source and sink profiles, thermodynamic targets for heat and power cogeneration can be set graphically. *Figure 21.20* shows the site source sink profiles and utility profiles for a site-wide analysis. On the left side of *Fig. 21.20a*, the gap between the process heat sources profile and the current steam generation profile shows that there is a potential to generate additional high-pressure steam through heat recovery from process heat sources. Similarly, on the right side of *Fig. 21.20a*, the gap between the process heat sink curve and the current steam consumption curve shows that much of the medium-pressure steam usage can be substituted by low-pressure steam to reduce the steam energy consumption.

Figure 21.20b shows the target for optimal steam generation through heat recovery from process heat sources and the target for optimal steam consumption (heat load and pressure levels). On the left side of *Fig. 21.20b*, the optimal additional high-pressure steam generation can be identified through shifting the existing steam generation profile toward process heat sources profile. This will effectively increase the heat integration between processes indirectly through the utility system, and reduce the need of external hot utility for steam generation. Similarly, on the right side of *Fig. 21.20b*, the optimal heat load and pressure levels of steam consumption can be targeted by shifting the existing steam consumption profile toward process heat sinks profile.

Typically, a site-wide pinch analysis can be carried out in two phases. The objective of first phase is to get a reliable target for overall, site-wide savings and to identify the potential area that is likely to yield greatest benefits during the following second phase. In this way, engineering hours are minimized both in phase 1, through the judicious selection of black- and gray-box processes, and in phase 2, by not having to study every data in detail. In phase 2, further project packages need to be developed, and the strategic total site road map can be constructed. After the work of phase 1, it is possible to establish the relationship between investment and benefit of all the projects in the site.

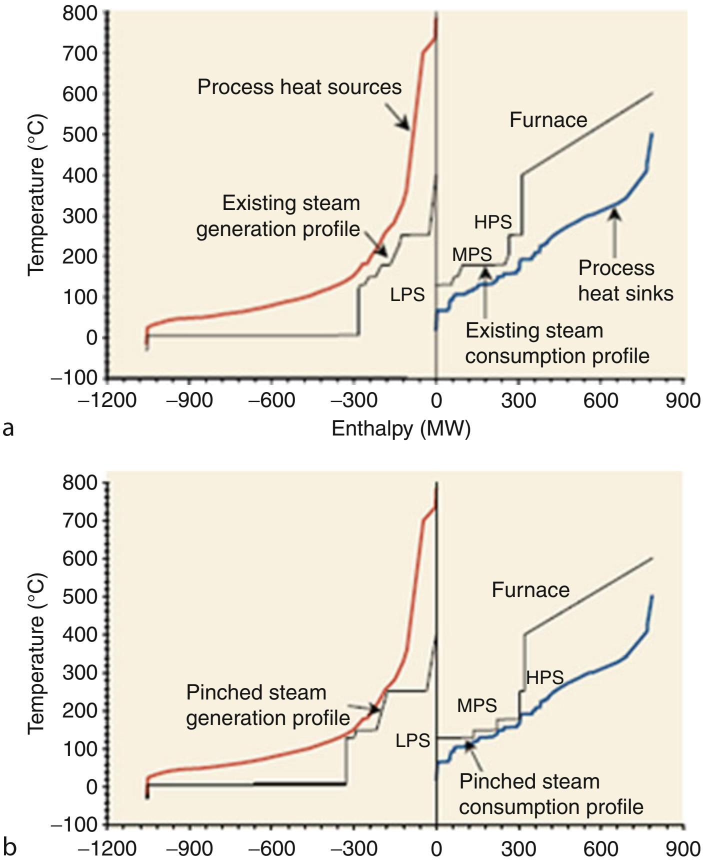

Fig. 21.20
(a) The existing total site profiles before targeting (b) Total site profiles after targeting [3]

Such a representation is called the road map for the site development. The road map includes project details such as savings, investment, effect on emissions, and the compatibility of projects with each other. Each route in a road map consists of a series of mutually compatible projects. Each project package is explored for its technical and economic feasibility. The road map forms a rigorous basis for the designer or planner to plan a route or a strategy for long-term site development on all energy-related issues.

As a summary, the key steps in total site pinch analysis can be listed as follows:

1. Individual process pinch analysis: Starting from heat and material balances of individual processes, pinch analysis establishes key options for process modifications, energy recovery (savings in noncentral utilities), and targets for multiple utilities. The grand composite curves are ready for use in total site analysis.
2. Total site pinch analysis: The site source sink profiles and the central utility generation and usage curves are constructed. They can help to set targets for the utility system

improvements and process-wise improvements. The assumptions of steam system in step (1), such as the pressure of steam mains, need to be reset if they are changed in this step (2).

3. Identification of specific projects and construction of road map: The targets obtained through previous steps need to be further implemented in detail. Then the specific projects are put together in a coherent plan involving alternative routes of compatible projects.
4. Final selection of project alternatives from total site road map.

The site-wide analysis technique can be a very powerful approach for oil refining, petrochemical, and iron and steel plants, as well as regional energy sectors. Some software applications based on this approach are currently available. The SuperTarget software package (KBC Energy Services, UK), allows engineers to undertake total site pinch analysis using its site module. Kazuo Matsuda et al. [2] applied the total site pinch analysis to one of the largest heavy chemical complexes in Japan which has 31 sites consisting of process industries including petrochemical, refinery, and power company. Their study demonstrates that despite the very high efficiency of the individual process plants in the complex, the area-wide pinch technology can identify a huge amount of energy-saving potential. In their study, a large amount of energy saving, 0.9×10^6 GJ/year, was achieved by the implement of area-wide integration projects.

An important innovation about the total site concept has been presented by Perry et al. [19], who extended this concept. Traditionally, a total site includes only a set of industrial processes. Perry et al. made a further improvement by including commercial and residential energy users into the total site concept. The resultant process collections are termed as locally integrated energy sectors.

Mathematical Programming Approach for HEN Design

Over the past decades, heat-integrated system and HEN design have been extensively studied. Most of the contributions to this research can be classified as either a sequential or a simultaneous synthesis method [20]. Generally speaking, mathematical programming represents a class of alternative techniques in spite of pinch analysis. Linear programming (LP) method and mixed integer linear programming (MILP) [10] are both sequential methods.

The simultaneous synthesis methods are primarily mixed integer nonlinear programming (MINLP) [21] formulations of HEN problems. The approach is based on a stage-wise superstructure representation that contains all possible network configurations and process stream matches. In each stage, potential heat exchange may take place between any pair of hot and cold streams. This MINLP model can simultaneously optimize and synthesize the capital and energy cost, and other structural features, as steam splitting and bypass design. While the MINLP can be formulated easily, unfortunately, it is frequently difficult to obtain converged solutions using the algorithms available today

in systems like GAMS, especially when the number of streams are large and the models are complex. It is beyond the scope of this text to cover in detail the approaches to formulating and solving MINLPs. However, in the next section of this chapter, disturbance propagation and rejection (DPR) embedded MINLP model is introduced for HEN design.

Disturbance Propagation and Control Modeling for the Design of Highly Controllable Heat-Integrated Systems

Traditionally, in most process synthesis activities, only the cost is considered when targeting the optimal solution. This practice can give rise to the designs at the minimum total annualized investment. Process operational issues, especially structural controllability, are usually not a concern in the design procedure, while only steady-state condition is considered. As a consequence, the operational controllability of the "optimal" design solution generated by the aforementioned traditional method may be questionable. In the worst case, an (economically) optimally designed process may not be operable, as shown in Yang et al. [22], where a real industrial example is described, where the originally designed HEN experiences various disturbances of temperatures and heat capacity flow rates in operation. Industrial practice has made it clear that process controllability should be part of the process synthesis work. This has led to the introduction of an active research area, called integration of process design and control (IPDC) [23–25].

The analysis of disturbance propagation (DP) and disturbance rejection (DR) is conducted extensively in flexibility and controllability analysis. Flexibility is a system's capability of absorbing long-term variations appearing at the inlet of process [26, 27]. Controllability is referred to the system's capability of withstanding short-term disturbances. Yang et al. [22, 28–30] introduced a simplified, first-principle-based modeling approach to evaluate DP in HENs, MENs, distillation networks, and heat-integrated reaction system design at the steady-state level. Integrating this quantitative analysis approach into traditional process synthesis can lead to the optimal design satisfying both economic and operational objectives.

Disturbance Propagation Modeling

The DP modeling approach introduced below is general and it will be integrated into a superstructure-based MINLP (mixed integer nonlinear programming) model, through a case study, to generate a cost-effective and highly controllable network.

In process synthesis stage, the precise information of process disturbance is usually unavailable. Meanwhile, a worst-case design is usually sufficient, though may not be optimal. Thus, the estimated maximum magnitude of each disturbance can be used instead. For a HEN operated at a given normal operating condition, the known types of

disturbances can be expressed as the maximum fluctuation of stream source temperature (δT^s) and that of heat capacity flow rate (δMc_p). After propagating these disturbances of input source streams, the resulting DP model can predict the stability of the target temperature of each stream by the obtained δT^t, which stands for the largest deviation from the normal operating target points. Yang et al. [22] developed a DP modeling methodology for a heat exchanger unit as well as a HEN that can contain any number of hot and cold streams. By neglecting the high-order differentiation terms and replacing the logarithmic mean temperature difference by an arithmetic mean term [31], the model can be simplified to a linear one and is summarized below.

Unit-based DP model. A DP model for a single heat transfer unit (HTU) can be written as follows:

$$\delta T^t = D_t \delta T^s + D_m \delta Mc_p \tag{21.1}$$

or

$$\begin{pmatrix} \delta T_h^t \\ \delta T_c^t \end{pmatrix} = \begin{pmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{pmatrix} \begin{pmatrix} \delta T_h^s \\ \delta T_c^s \end{pmatrix} + \begin{pmatrix} (2-\alpha)\alpha_h & -\alpha_c \alpha \\ \beta \alpha_h & -\alpha_c(2-\beta) \end{pmatrix} \begin{pmatrix} \delta MC_{p_h} \\ \delta MC_{p_c} \end{pmatrix} \tag{21.2}$$

where

$$\alpha = \frac{T_h^s - T_h^t}{T_h^s - T_c^s} \tag{21.3}$$

$$\beta = \frac{T_c^t - T_c^s}{T_h^s - T_c^s} \tag{21.4}$$

$$\alpha_h = \frac{T_h^s - T_h^t}{2MC_{p_h}} \tag{21.5}$$

$$\alpha_c = \frac{T_c^t - T_c^s}{2MC_{p_c}} \tag{21.6}$$

where D_t and D_m are temperature and heat capacity flow rate related disturbance propagation matrix, respectively; T and δT are the stream temperature and temperature fluctuation, respectively; Mc_p and δMc_p are the heat capacity flow rate and its fluctuation, respectively; superscripts s and t refer to source and target, respectively; and h and c refer to hot and cold stream, respectively. The above model can be used to provide a quick and accurate quantification of DP through the propagation in a heat exchanger.

System DP model. The unit-based DP model in ➋ Eq. 21.1 can be applied to any heat transfer unit (HTU) in a HEN. Thus, the DP model for the i-th HTU, named E_i, in a HEN can be expressed as:

$$\delta T_{E_i}^{\mathrm{out}} = D_{t_{E_t}} \delta T_{E_i}^{\mathrm{in}} + D_{m_{E_i}} \delta Mc_{p_{E_i}} \tag{21.7}$$

If a HEN contains N_e heat exchangers, a system DP model can be established directly by lumping all the single unit-based models in the sequence of exchanger numbers. This procedure yields the following equation:

$$\delta T^{*\mathrm{out}} = D^*_{t_E}\delta T^{*\mathrm{in}} + D^*_{m_E}\delta Mc^*_p \tag{21.8}$$

where

$$\delta T^{*\mathrm{in}} = \left[\left(\delta T^{\mathrm{in}}_{E_1}\right)^T \left(\delta T^{\mathrm{in}}_{E_2}\right)^T - \left(\delta T^{\mathrm{in}}_{E_{N_e}}\right)^T\right]^T, \tag{21.9}$$

$$\delta T^{*\mathrm{out}} = \left[\left(\delta T^{\mathrm{out}}_{E_1}\right)^T \left(\delta T^{\mathrm{out}}_{E_2}\right)^T - \left(\delta T^{\mathrm{out}}_{E_{N_e}}\right)^T\right]^T, \tag{21.10}$$

$$\delta Mc^*_p = \left[\left(\delta Mc_{P_{E_1}}\right)^T \left(\delta Mc_{P_{E_2}}\right)^T - \left(\delta Mc_{P_{E_{N_e}}}\right)^T\right]^T, \tag{21.11}$$

$$D^*_{t_E} = \mathrm{diag}\left\{D_{t_{E_1}}, D_{t_{E_2}}, \cdots, D_{t_{E_{N_e}}}\right\}, \tag{21.12}$$

$$D^*_{m_E} = \mathrm{diag}\left\{D_{m_{E_1}}, D_{m_{E_2}}, \cdots, D_{m_{E_{N_e}}}\right\}, \tag{21.13}$$

The superscript T in equations designates the transpose operation of corresponding matrix, which interchanges the rows and columns of matrix. The "diag" in Eqs. 21.12 and 21.13 means the matrix $D^*_{t_E}$ and $D^*_{m_E}$ are diagonal matrix, which is a square matrix whose elements outside the main diagonal are all zero. The dimensions of vectors $\delta T^{*\mathrm{in}}$, $T^{*\mathrm{out}}$, and δMC^*_p are all $2N_e \times 1$, and the $D^*_{t_E}$ and $D^*_{m_E}$ are both $2N_e \times 2N_e$ matrices. It is needed to point out that $\delta T^{*\mathrm{in}}$ and $\delta T^{*\mathrm{out}}$ contain a number of N_m intermediate temperatures. An intermediate temperature is the temperature of a stream between two adjacent heat transfer units (HTUs). N_m can be calculated by the following Eq. 21.14

$$N_m = 2N_e - N_s - N_{\mathrm{split}} \tag{21.14}$$

where N_e is the number of HTUs; N_s is the total number of hot streams and cold streams; N_{split} is the total number of stream branches after splitting.

After several steps of mathematical processing, a general system DP model can be derived as bellow:

$$\delta T^t = \underline{D_t}\delta T^s + \underline{D_m}\delta Mc_p \tag{21.15}$$

where

$$\underline{D_t} = D_{t11} + D_{t12}(I - D_{t22})^{-1}D_{t21} \tag{21.16}$$

$$\underline{D_m} = D_{m1} + D_{t12}(I - D_{t22})^{-1}D_{m2} \tag{21.17}$$

Those underbars in the equations do not have any mathematical meaning and are just symbols to differentiate from other matrix variables. For the detailed deduction of this model, please refer to the work of Yang et al. [32].

DP-based network structure representation. To derive those matrices in the DP model, a structural matrix S, whose dimension is $(2N_e - N_{split}) \times 2N_e$, should be constructed. Matrix S can be decomposed into two sub-matrices, $S_1(N_s \times 2N_e)$ and $S_2(N_m \times 2N_e)$, whose definitions are given below.

In sub-matrix S_1, each row is designed for a hot or cold stream, and the columns are divided into N_e pairs. Each pair is assigned for a specific heat transfer unit (HTU). In each pair, the left column corresponds to the hot stream going through the HTU, and the right column corresponds to the cold stream through the unit. A stream may be split into a number of branches, going through different HTUs and mixing together. In this case, the splitting ratios are reflected by the matrix elements corresponding to the streams. Each element has a value between 0 and 1, where 0 represents streams not going through the units; a fraction represents the splitting portion going through the unit; and 1 means the stream going through units without splitting.

In sub-matrix S_2, each row represents the intermediate streams between two adjacent HTUs. The definition of columns are the same as sub-matrix S_1. Each element of matrix S_2 represents the connection modes of the intermediate stream with an HTU. [1], [1], or 0 are assigned to the element to represent an intermediate stream entering, leaving or not going through a HTU, respectively.

DP model embedded HEN synthesis approach. HEN synthesis can be fulfilled by mixed integer nonlinear programming (MINLP) method, following the procedures of network representation, mathematical optimization model formulation, and optimal solution identification. The DP model introduced above can be integrated in the optimization model to take account of controllability issues in HEN design.

Problem statement. In a HEN synthesis problem, there are a set I of hot process streams, a set J of cold process streams, and a set K of superstructure stages. Each hot or cold process stream has a specified heat capacity flow rate, and their inlet and outlet temperatures are also specified exactly or given as inequalities. A set of hot and cold utilities, along with their temperatures are also known. Meanwhile, the predicted max–min source temperature disturbance and flow rate fluctuations are also given along with the permissible target temperature fluctuations. The objective of the synthesis is to determine a network structure with the minimum total annual cost (TAC) satisfying the permissible target temperature fluctuations requirement.

Stream-based superstructure. The first step of the synthesis is constructing a stream-based superstructure. A HEN superstructure can be developed by a graph-theoretical approach [12]. *Figure 21.21* shows a two-stage superstructure for a two hot–two cold stream synthesis problem, which will be studied in this case. All units and their inputs and outputs are represented as a set of nodes in the graph, where all possible connections are linked between pairs of units. The key elements of a superstructure are HTUs, mixers, and splitters. A HTU is denoted as a large circle, while a mixer or splitter is denoted as a small dot. Each HTU has a splitter at its inlet and a mixer at its outlet.

Problem formulation. After the construction of HEN superstructure, the next step is to formulate the synthesis problem with mathematical equations.

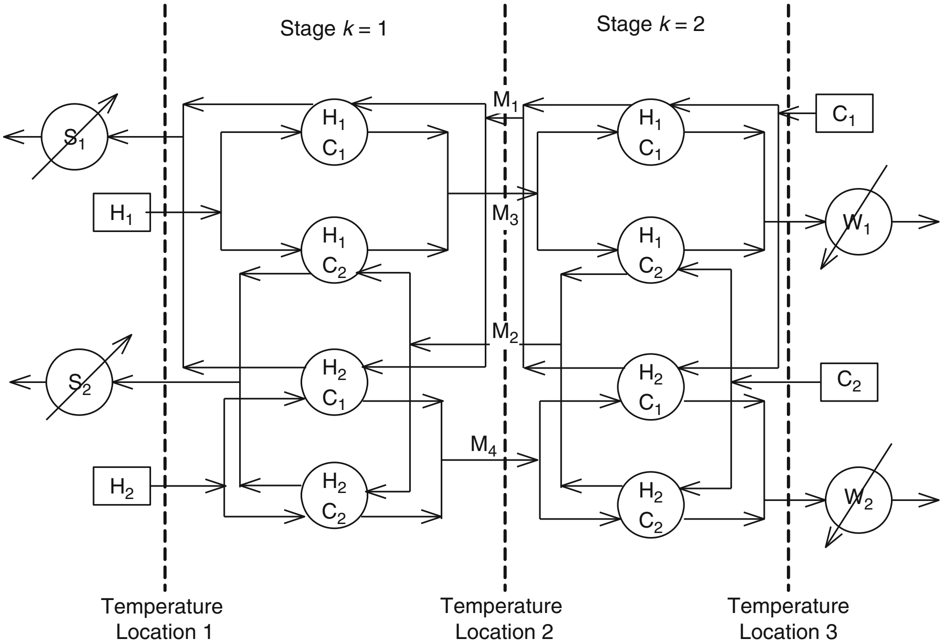

Fig. 21.21
Two-stage superstructure for two hot streams and two cold streams [32]

Objective function. The total annual cost (TAC) is the combination of the utilities cost and heat exchangers related cost, such as the cold utility cost, hot utility cost, fixed charges, and area cost for heat exchangers between streams. TAC should be minimized and can be formulated as [32]:

$$\begin{aligned} \min & \sum_{i\in I} C_{CU} Q_{cu,i} + \sum_{j\in J} C_{HU} Q_{hu,j} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} CF_{i,j} y_{i,j,k} + \sum_{i\in I} CF_{cu,i} y_{cu,i} + \sum_{j\in J} CF_{hu,j} y_{hu,j} \\ & + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} C_{i,j}\left(\frac{Q_{i,j,k}}{U_{i,j}[\Delta T_{i,j,k}\Delta T_{i,j,k+1}(\Delta T_{i,j,k}+\Delta T_{i,j,k+1})/2]^{1/3}}\right)^{0.6} \\ & + \sum_{i\in I} C_{i,cu} + \left(\frac{Q_{cu,i}}{U_{cu,i}[\Delta T_{cu,i}(T_i^t - T_{cu}^s)(\Delta T_{cu,i} + T_i^t - T_{cu}^s)/2]^{1/3}}\right)^{0.6} \\ & \sum_{j\in J} C_{j,cu} + \left(\frac{Q_{hu,j}}{U_{hu,j}[\Delta T_{hu,j}(T_{hu}^s - T_j^t)(\Delta T_{hu,j} + T_{hu}^s - T_j^t)/2]^{1/3}}\right)^{0.6} \end{aligned} \tag{21.18}$$

where C_{CU} is the per unit cost of cold utility; $Q_{cu,\,i}$ stands for the heat exchanged between hot stream i and the cold utility; C_{HU} is the per unit cost of hot utility; $Q_{hu,\,j}$ stands for the heat exchanged between cold stream j and the hot utility; CF is the fixed charge for heat exchangers; C is the area cost coefficient; the exponent 0.6 in this equation is a constant used by many researchers to analyze the area cost of heat exchangers; T^s and T^t are inlet

and outlet temperatures, respectively; U is the heat transfer coefficient; $Q_{i,\ j,\ k}$ is the heat exchanged between hot process stream i and cold process stream j in stage k; $\Delta T_{i,\ j,\ k}$, is the temperature approach for the match of hot stream i and cold process stream j in stage k; $\Delta T_{cu,\ i}$ is the temperature approach for the match of hot stream i and the cold utility; $\Delta T_{hu,\ j}$ is the temperature approach for the match of cold process stream j and hot utility; variable $y_{i,\ j,\ k}$ stands for the existence of a match between hot process stream i and cold process stream j in stage k; $y_{cu,\ i}$ stands for the existence of a match between hot stream process i and cold utility; and $y_{hu,\ j}$ stands for the existence of a match between cold stream process j and hot utility. The binary variables represent the existence of unit for a match and the values are either 1 or 0.

$$y_{i,j,k}, y_{cu,i}, y_{hu,j} \in \{0,1\}, \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{21.19}$$

Constraints. This MINLP problem should be subject to the following constraints.

Energy balance constraints. The overall energy balance for each process streams should be observed. For example, the amount of energy each hot (cold) process stream releases (obtains) by the difference of source and target stream temperature should be equal to the sum of heat transferred between process streams and heat transferred to (from) cold utilities (hot utilities).

Also, the energy balance for each stream is each superstructure stage and energy balance for the utility streams should be respected.

Temperature feasibility constraints. The temperature of each stream should decrease monotonically along with the temperature locations.

Logical constraints. The temperature approach between the streams that exchanged heat should not exceed the maximum temperature difference. Meanwhile, the exchanged heat of process streams and utilities cannot exceed an upper limit.

System controllability constraints. Besides the above constraints, the target temperature fluctuations of streams should be limited in permissible ranges, which are the controllability-related constraints.

$$\delta T_{max}^{t(-)} \le \delta \underline{T}^{t} \le \delta T_{max}^{t(+)} \tag{21.20}$$

where $\delta \underline{T}^{t}$ is the vector for target temperature fluctuations, $\delta T_{max}^{t(-)}$ and $\delta T_{max}^{t(+)}$ are vectors for the maximum negative and positive target temperature fluctuations, respectively.

The DP-based network structure matrix S can be constructed according to the approach introduced in the previous section. Then based on this structure matrix S and the binary variables, a HEN system DP model can be constructed as introduced before. Through the system DP model, the target temperature fluctuations $\delta \underline{T}^{t}$ can be obtained from the source temperature disturbances $\delta \underline{T}^{s}$ and source heat capacity flow rate disturbances $\underline{Mc_p}$.

Optimal solution identification. After the formulation of objective function and various constraints, the last step in this synthesis approach is the optimization of the model. This DP-embedded MINLP model can be solved using the general algebraic modeling system (GAMS).

Case application of DP-embedded HEN synthesis approach. Yan et al. [32] studied the case of Yee et al. ([21]) for the incorporation of DP into the HEN design procedure.

Table 21.2

Stream data for the synthesis problem [32]

Stream	T^s (°C)	T^t (°C)	Mc_p (kW/°C)	$\delta T^{s(+)}$ (°C)	$\delta T^{s(-)}$ (°C)
Hot 1	180	75	30	5	0
Hot 2	240	60	40	0	0
Cold 1	40	230	35	0	−5
Cold 2	120	300	20	0	−5
The heat transfer coefficients: $U_{i,j} = U_{cu,i}$ = 0.8 kW/(m^2·°C); $U_{hu,j}$ = 1.2 kW/(m^2·°C)					
The per unit cost of utilities: C_{CU} = 20 \$/(kW·year); C_{HU} = 80 \$/(kW·year)					
The area cost coefficients: $C_{i,j} = C_{i,cu}$ = 1,000; $C_{hu,j}$ = 1,200					

This design problem has two hot streams and two cold streams. The design data including the disturbance information are listed in *Table 21.2*. The stage-wise superstructure is already shown in *Fig. 21.21*. There are 12 possible matches and therefore 12 binary variables. According to this superstructure, a structure matrix S is also generated and listed in *Table 21.3*. The "M" labeled stream in *Table 21.3* stands for the intermediate stream between two adjacent heat transfer units. In this case, three scenarios are studied and each has a different control requirement. In each scenario, the control requirements, which are the maximum negative and positive target temperature fluctuations $\delta T^{t(-)}_{max}$ and $\delta T^{t(+)}_{max}$, act as one of the constraints. The optimal HEN of this scenario can be obtained by solving the DP-embedded MINLP problem using GAMS.

For further detailed calculations, please refer to the work of Yan et al. and only the results are provided here. *Table 21.2* listed the control requirements, the actual temperature fluctuations, and the TAC of each scenario. *Figures 21.22–21.24* give the optimal HEN solution of each scenario under different control specifications. The symbol "E" in these figures represents the heat exchangers.

Comparing the three optimal solutions, it is obvious that solution A in scenario I has the simplest HEN structure (*Fig. 21.22*) and the minimum TAC ($ 450,072 in *Table 21.2*). This is because in scenario I, there are no constraints imposed on the maximum negative and positive target temperature fluctuations $\delta T^{t(-)}_{max}$ and $\delta T^{t(+)}_{max}$ and actually this is the traditional synthesis case where no control issues are considered. However, when the strict control requirements are specified, this optimal solution may not qualify. For example, in scenario III, the control requirement $\delta T^{t(\pm)}_{max}$ of cold stream 2 is within the range of ± 1°C, which is far beyond the actual temperature fluctuations of $(-3.3, 6.6)$°C in scenario I. This indicates solution A will not meet the control requirements of scenario III and this indicates that integrating DP model into the HEN design procedure can generate the optimal result which meets the control requirements. Plus, different control specifications can be imposed on the synthesis problem according to the real process. Comparing scenarios II and III, stricter control requirements are imposed on cold stream 2 and hot stream 1 and a higher TAC is needed in scenario III. The higher TAC is kind of the trade-off for stricter control requirements (*Table 21.4*).

Table 21.3

Structural matrix for the superstructure of case study [32]

Stream	HTU_1		HTU_2		HTU_3		HTU_4		HTU_5		HTU_6		HTU_7		HTU_8	
	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C
H_1	$\frac{Q_{1,1,1}}{Q_{1,1,1}+Q_{1,2,1}}$	0	$\frac{Q_{1,2,1}}{Q_{1,1,1}+Q_{1,2,1}}$	0	0	0	0	0	$\frac{Q_{1,1,2}}{Q_{1,1,2}+Q_{1,2,2}}$	0	$\frac{Q_{1,2,2}}{Q_{1,1,2}+Q_{1,2,2}}$	0	0	0	0	0
H_2	0	0	0	0	$\frac{Q_{2,1,1}}{Q_{2,1,1}+Q_{2,2,1}}$	0	$\frac{Q_{2,2,1}}{Q_{2,1,1}+Q_{2,2,1}}$	0	0	0	0	0	$\frac{Q_{2,1,2}}{Q_{2,1,2}+Q_{2,2,2}}$	0	$\frac{Q_{2,2,2}}{Q_{2,1,2}+Q_{2,2,2}}$	0
C_1	0	$\frac{Q_{1,1,1}}{Q_{1,1,1}+Q_{2,1,1}}$	0	0	0	$\frac{Q_{2,1,1}}{Q_{1,1,1}+Q_{2,1,1}}$	0	0	0	$\frac{Q_{1,1,2}}{Q_{1,1,2}+Q_{2,1,2}}$	0	0	0	$\frac{Q_{2,1,2}}{Q_{1,1,2}+Q_{2,1,2}}$	0	0
C_2	0	0	0	$\frac{Q_{1,2,1}}{Q_{1,2,1}+Q_{2,2,1}}$	0	0	0	$\frac{Q_{2,2,1}}{Q_{1,2,1}+Q_{2,2,1}}$	0	0	0	$\frac{Q_{1,2,2}}{Q_{1,2,2}+Q_{2,2,2}}$	0	0	0	$\frac{Q_{2,2,2}}{Q_{1,2,2}+Q_{2,2,2}}$
M_1	{1}	0	{1}	0	0	0	0	0	[1]	0	[1]	0	0	0	0	0
M_2	0	0	0	0	{1}	0	{1}	0	0	0	0	0	[1]	0	[1]	0
M_3	0	[1]	0	0	0	[1]	0	0	0	{1}	0	0	0	{1}	0	0
M_4	0	0	0	[1]	0	0	0	[1]	0	0	0	{1}	0	0	0	{1}

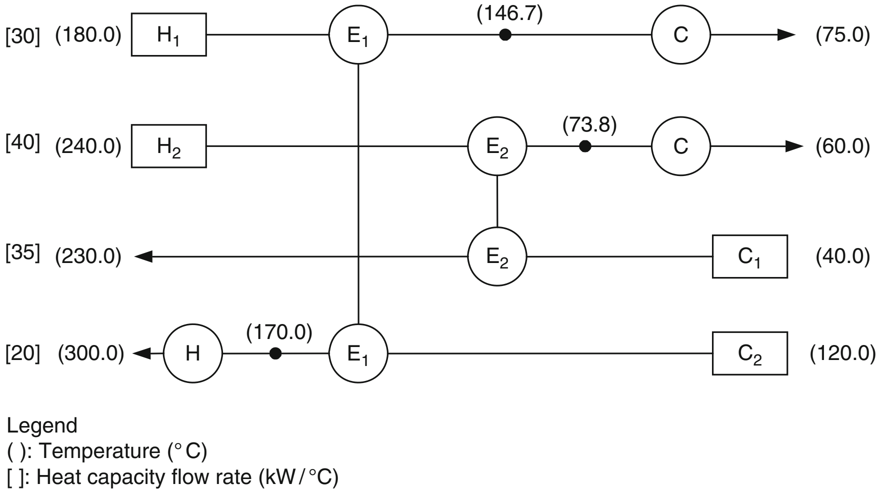

Fig. 21.22
Solution A for the HEN synthesis problem in scenario I [32]

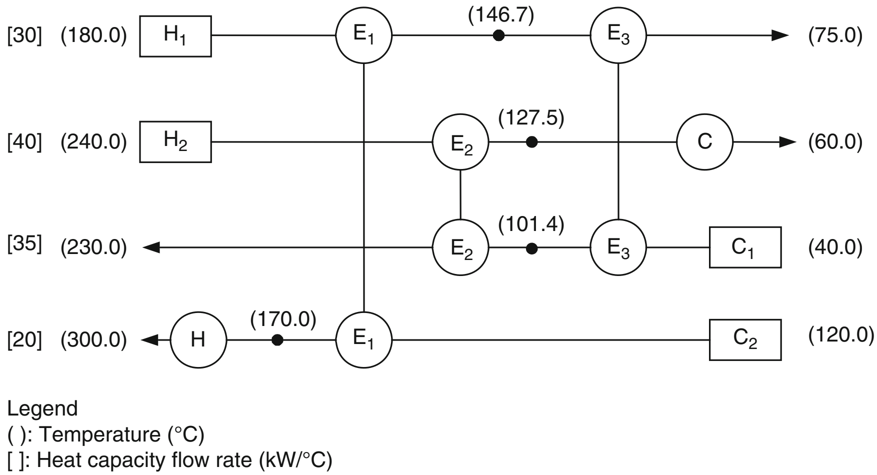

Fig. 21.23
Solution B for the HEN synthesis problem in scenario Π [32]

Disturbance Propagation and Control (DP&C) Model Embedded Synthesis Approach

The DP model introduced above can be used to quickly estimate the maximum deviation of system outputs under various types of disturbances. However, the DP models do not consider any control actions for disturbance rejection (DR). This can lead to

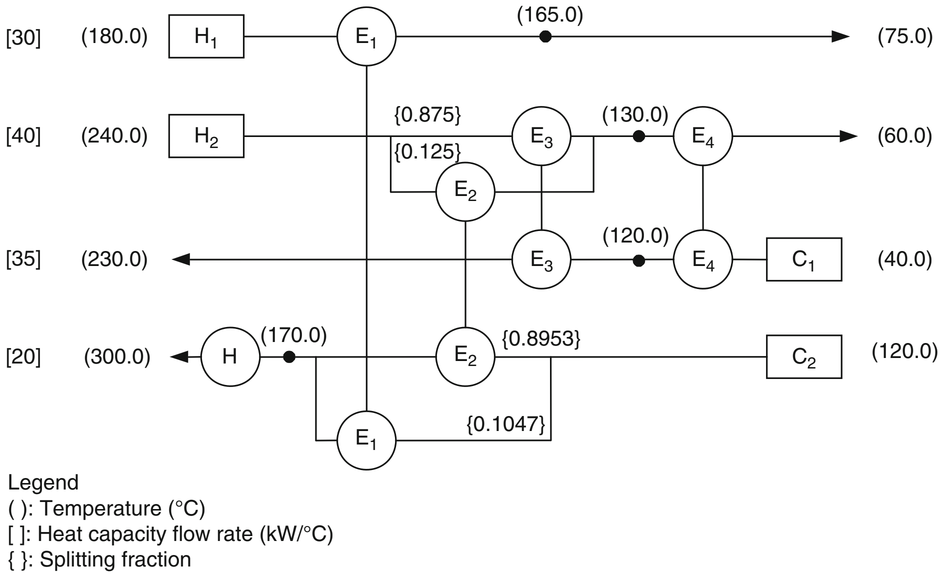

Fig. 21.24
Solution C for the HEN synthesis problem in scenario Ш [32]

Table 21.4
Comparison of the solutions under different control requirements [32]

Streams	Case I (solution A)		Case II (solution B)		Case III (solution C)	
	$\delta T^{t(\pm)}_{max}$ (°C)	δT^{t} (°C)	$\delta T^{t(\pm)}_{max}$ (°C)	δT^{t} (°C)	$\delta T^{t(\pm)}_{max}$ (°C)	δT^{t} (°C)
Hot 1	–	3.7/−4.2	±6	2.0/−5.5	±2	1.0/−1.3
Hot 2	–	0.0/−4.2	±4	2.0/−4.0	±4	0.6/−3.9
Cold 1	–	0.0/−0.3	±1	0.2/−0.4	±3	1.0/−2.8
Cold 2	–	6.6/−3.3	±10	6.6/−3.3	±1	0.9/−0.8
TAC ($/year)	450,072		450,759		468,013	

a conservative network design. In operation, a HEN is always controlled through regulating bypass flow rates associated with heat exchangers. Thus, Yan et al. [31] further extend Yang's DP model to a disturbance propagation and control (DP&C) model where control actions are taken into account. This model can be embedded into a HEN design procedure to optimally select the locations and nominal fractions of bypasses with the minimum penalty on capital cost.

The system DP&C model is expressed below. For the detailed derivations, please refer to the work of Yan et al. [31].

$$\delta \underline{T}^t = \underline{B}\delta \underline{f} + \underline{D_t}\delta \underline{T}^s + \underline{D_m}\delta \underline{Mc_p} \tag{21.21}$$

where

$$\underline{B} = B_1 + D_{t_{12}}(\mathrm{I} - D_{t_{22}})^{-1}B_2 \tag{21.22}$$

$$\underline{D_t} = D_{t_{11}} + D_{t_{12}}\left(\mathrm{I} - D_{t_{22}}\right)^{-1}D_{t_{21}} = \left(\underline{D_{t_h}}^T \underline{D_{t_c}}^T\right)^T \tag{21.23}$$

$$\underline{D_m} = D_{m_1} + D_{t_{12}}(\mathrm{I} - D_{t_{22}})^{-1}D_{m_2} = \left(\underline{D_{m_h}}^T \underline{D_{m_c}}^T\right)^T \tag{21.24}$$

$\delta \underline{T}^t$ and $\delta \underline{T}^s$ are vectors of maximum stream temperature deviation for the target and source temperature, respectively; $\underline{B}$ is the process-gain matrix; $\delta \underline{f}$ is the vector of maximum fluctuations of bypass nominal fractions; $\underline{D_t}$, $\underline{D_m}$, B_1, B_2 etc. are relative matrices.

Disturbance rejection with minimum economic penalty. While a bypass of a heat exchanger can help to reject disturbances, its installation must cause an increment of heat transfer area and the capital cost. A trade-off between the DR and cost must be made in the bypass selection. *Figure 21.25* illustrates how the stream target temperature fluctuation (δT^t) and the increment heat transfer area ($\Delta A_E/A_E$) are related to the nominal fraction of a bypass (f_E). The nominal fraction of a bypass (f_E), can be selected from 0 (no bypass) to the upper limit $f_E^{(\lim)}$. As shown in *Fig. 21.25*, when f_E increases, δT^t will

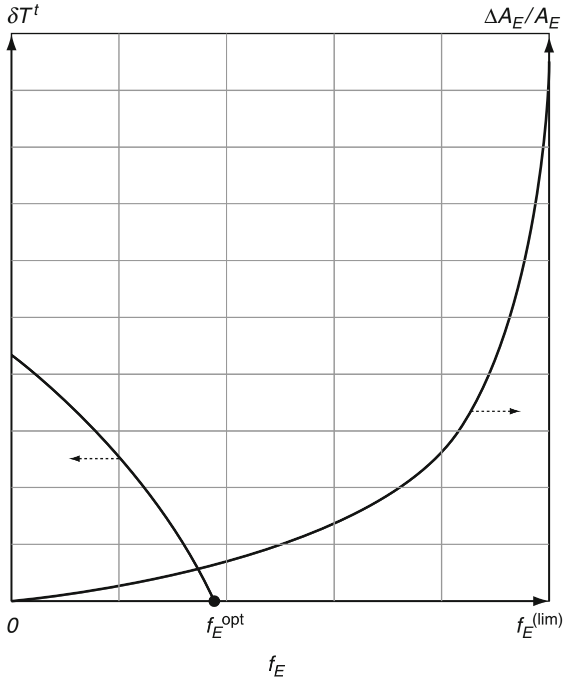

Fig. 21.25
Relationship of target temperature, heat transfer area, and bypass fraction [31]

decrease, while $\Delta A_E/A_E$ will increase. In this study, the optimal solution is defined as the one realizing complete disturbance rejection at the steady state, and with minimum increment of heat transfer areas. Any nominal fraction value below the optimal value f_E^{opt} will not realize complete DR. Meanwhile any value above f_E^{opt} will have more area increment with the same complete DR level, and this is certainly not desirable.

Case study: design of bypasses and control loops for a four-stream HEN. Yan et al. [31] developed an iterative design procedure to determine the optimal locations and nominal fractions of bypasses in a HEN design and applied this method to a four-stream HEN design case previously studied by Yee and Grossmann [21]. For simplicity, only the problem statement and the solution are provided here to demonstrate the efficacy of this approach.

Table 21.5 and *Fig. 21.26* show the steady-state design data as well as source disturbance information and control requirements of the selected case.

Table 21.5
Design data for the four-stream HEN synthesis problem [31]

Stream no.	T^s (K)	T^t (K)	Mc_p (kW/K)	$\delta T^{s(+)}$ (K)	$\delta T^{s(-)}$ (K)	$\delta T_{max}^{t(+)}$ (K)	$\delta T_{max}^{t(-)}$ (K)
H_1	620.0	385.0	10.0	5	0	0	0
H_2	720.0	400.0	15.0	0	0	5.5	−5.5
C_1	300.0	560.0	20.0	0	−5	0	0
C_2	280.0	340.0	30.0	0	−5	4.0	−4.0

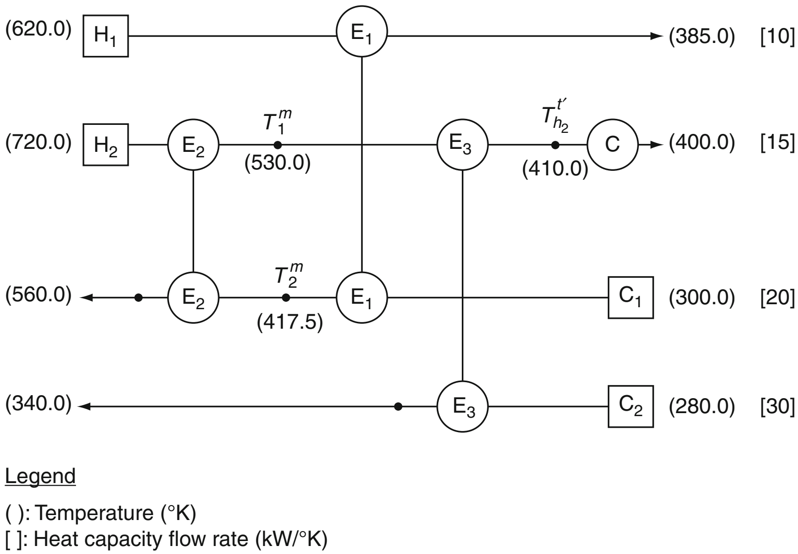

Fig. 21.26
Original four-stream HEN design [33]

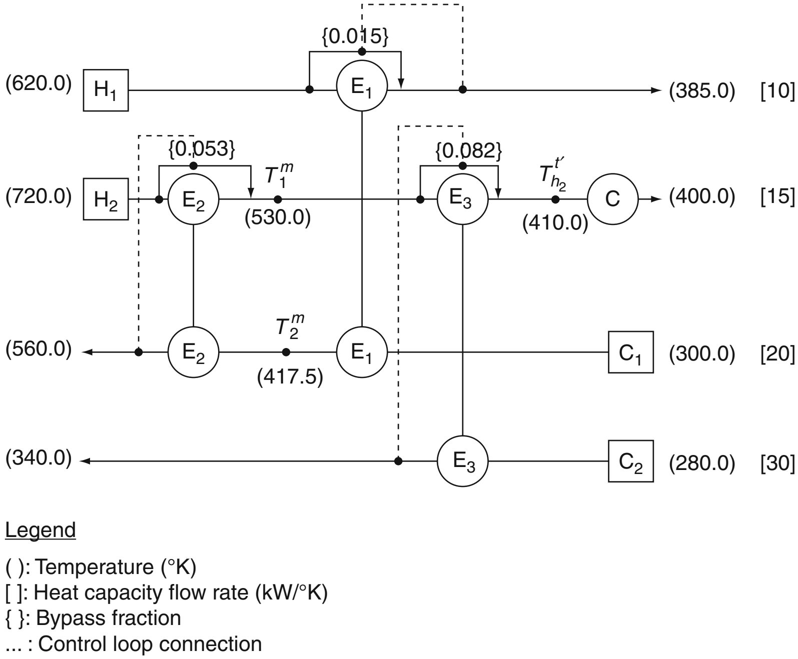

Fig. 21.27
Optimal bypass design for the HEN by the DP&C approach [31]

The resulting optimal bypass design with control loops by the DP&C approach is shown in Fig. 21.27. Uztruk and Akman [33] also studied the same problem and their result is shown in Fig. 21.28. Table 21.6 compares the different design results in total costs. The design solution by DP&C model is 6% cheaper than that by Uzturk and Akman. In addition, the RGA (relative gain array) analysis reveals that the solution by DP&C method has no system interaction among loops at steady state. By contrast, the design in Fig. 21.28 has considerable interactions among loops.

To sum up, the disturbance propagation and control (DP&C) method can quantify the disturbance propagation and disturbance rejection by using bypasses in the HEN design process. It can help to design the fewest bypasses with their nominal fractions for complete disturbance rejection with minimum economic penalty. The application strongly demonstrates the robustness and efficacy of this DP&C-based HEN design approach.

Emissions Targeting and Planning: CO_2 Emissions Pinch Analysis (CEPA)

Emission targeting by pinch analysis has been reported by Linnhoff and Dhole [8] using the total site analysis concept. Total site in their work refers to industrial systems incorporating several processes, which are serviced by a central energy utility system. Although emission

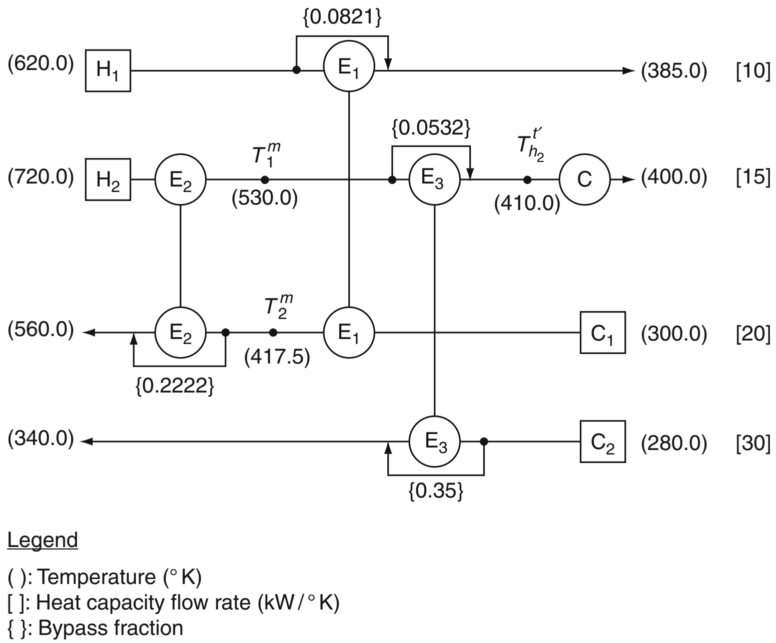

Fig. 21.28
Bypass design for the same HEN by Uzturk and Arkam [33]

Table 21.6
Comparison of different design results [31]

Heat exchanger	Original design (no bypass), area (m^2)	DP&C design (with bypass), area (m^2)	Uzturk and Akman design (with bypass), area (m^2)
E_1	34.7	35.4	39.1
E_2	42.3	44.3	49.2
E_3	22.8	23.7	25.8
ΣE_i	99.8	103.4	114.1
Cost	$24,386	$24,905	$26,408

targeting by pinch analysis was introduced in those studies, the early applications were limited to within industrial facilities. Tan and Foo [34] reformulated the traditional "total site" concept [8, 18, 35] and presented a novel application of pinch analysis for the preliminary planning of a country's energy sector. The carbon emissions pinch analysis (CEPA) was first developed by Tan & Foo and coworkers [34, 36, 37] for emissions targeting and reduction from industrial sites to macroscales (e.g., regional or national energy sectors).

Crilly and Zhelev utilized the CEPA method to analyze the Irish electricity sector [38]. Detailed description of the procedure for implementing the CEPA methodology can be found in [38]. The following is a brief illustration of the novel method.

When planning energy sectors, it occurs very often that emission constraints will present. This is especially common in the industrialized countries such as Germany and Ireland where CO_2 emissions limits are applied during the Kyoto/post-Kyoto setting. Thus, the problem arises when considering how to identify energy allocation schemes to meet the specified emission limits. If only environmental issues are considered, it is naturally desirable to maximize the use of low-carbon or zero-carbon energy sources, such as wind, hydroelectric, solar, biomass energy, etc. However, in real-world planning scenarios, economic issues need to be considered. Due to the high cost of renewable energy sources mentioned above, it is often desirable to determine the minimum amount of low-carbon or zero-carbon energy sources required to meet the national or regional emission limits and energy demand, which is known as the defined pinch point. The CEPA method can be used to determine the minimum quantity of low-carbon or zero-carbon energy sources needed and the energy allocation scheme among different energy resources in order to meet the specified emission limits and energy demand.

Ireland's electricity sector. In Ireland, GHG emissions come from various industrial sectors, including electricity generation, transportation, other manufacturing and service industries, as well as agricultural and waste-treatment sectors. The emissions in 2005 have an overall 25.48% increase as compared with the 1990 level. This amount is far above Ireland's permissible 13% increase in overall GHG emissions under the European Union (EU)'s burden-sharing agreement on the Kyoto protocol. For Ireland's electricity sector, it contributed a 23.33% share of Ireland's overall GHG emissions in 2005 (21.40% in 1990) and took a substantial 32.66% of Ireland's total primary energy requirement (TPER), according to the publications from the government. In 2005, the TPER can be classified using the following actual energy resource (AER) mix [38]:

1. Fossil fuel: natural gas (NG) ~ 40.09%, coal (C) ~ 27.77%, oil (O) ~ 15.16%, peat (P) ~ 10.02%
2. Electricity: Imported electricity (IE) from Scotland ~ 3.45%
3. Renewable energy sources (RESs): landfill gas, biomass, and other biogas ~ 0.57%, hydro ~ 1.06%, wind ~ 1.88%

In the short-to-medium future of Ireland's electricity sector, a well-designed optimal energy resource (OER) mix is required to satisfy both the energy needs and emissions limit. The renewable energy source-electricity (RES-E) has its disadvantages, such as high cost, limited public acceptability, inherent intermittency/variability, lack of predictability and poor reliability, etc. Thus, only the absolute minimum amount of RES-E should be employed in the optimal energy resource (OER) mix for the sector.

Application of CEPA. The basis of the approach is the construction of the composite curves of both the demand and the supply. These composite curves are then manipulated and shifted depending on the desired objectives. Crilly and Zhelev applied the CEPA to the electricity sector based on the data sources from the Sustainable Energy Authority of Ireland (SEAI), which is set up by the Ireland government as its national energy authority. The data for the actual energy resource (AER) mix in 2005 is shown in *Table 21.7*. The energy demand (consumption) and resource (supply) composite curves (CC) before shifting are

Table 21.7

The past and forecasted AER mixes and OER mixes for the sector in 2005 and 2010, respectively [38]

	RESs	NG	Oil	Coal	Peat	IE	Total
EF $\left(t\frac{CO_{2(e)}}{TJ}\right)$	0	56.8	75.6	94.6	116.7	120.0	_
Past AER mix_{2005}							
% of Total TJ/year	3.51	40.09	15.16	27.77	10.02	3.45	100.00
TJ/year	7,494	85,578	32,364	59,285	21,395	7,369	213,485
Mt CO_2(e)/year	0.00	4.86	2.45	5.61	2.50	0.88	16.30 > KL_{2005}
Past OER mix_{2005} (by CEPA)							
% of Total TJ/year	9.83	40.09	15.16	27.77	7.15	0.00	100.00
TJ/year	20,994	85,578	32,364	59,285	15,264	0.00	213,485
Mt CO_2(e)/year	0.00	4.86	2.45	5.61	1.78	0.00	14.70 = KL_{2005}
Projected AER mix_{2010}							
% of Total TJ/year	7.20	56.52	0.14	30.74	2.38	3.02	100.00
TJ/year	17,585	137,997	335	75,069	5,820	7,369	244,175
Mt CO_2(e)/year	0.00	7.84	0.03	7.10	0.68	0.88	16.53 > KL_{2010}
Projected OER mix_{2010} (by CEPA)							
% of Total TJ/year	8.02	56.52	0.14	30.74	2.38	2.20	100.00
TJ/year	19,585	137,997	335	75,069	5,820	5,369	244,175
Mt CO_2(e)/year	0.00	7.84	0.03	7.10	0.68	0.64	16.29 = KL_{2010}

plotted in *Fig. 21.29*. More specifically, the figure depicts a correlation between the amount of CO_2 or $CO_{2(equivalent)}$ per unit time and the amount of energy per unit time. It shows a slope of the amount of CO_2 per unit energy for any line segments, which is also the emission factor. The resource composite curve is constructed by plotting cumulatively the quantity of electricity generated for the several fuel resources against total emissions from those resources. The emission factor (EF) (i.e., the amount of emissions produced per unit of electricity, $t\frac{CO_{2(e)}}{TJ}$) for each energy resources is also provided in *Table 21.7*. The fuel source with the lowest emission factor is plotted first, followed by the next lowest and so on. In this resource composite curve, the renewable energy source is plotted first, followed by natural gas, oil, coal, peat, and imported electricity. The slope of each line segment is equal to the emission factor of corresponding energy resource. All emissions factors are expressed as carbon equivalent and include all relevant greenhouse gases.

Ireland permitted an increase of its overall GHG emissions by no more than 13% per year during 2008–2012, as compared to the baseline year of 1990, which is 55.75 Mt $CO_{2(e)}$. Thus, Ireland's environmental protection agency determined a leveled-out Kyoto limit (KL) of 62.99 Mt $CO_{2(e)}$ for each year between 2008 and 2012. The Kyoto limit KL_{2005} for 2005 is 61.78 Mt $CO_{2(e)}$ by the principle of interpolation. Because the electricity sector had a 23.79% share of the actual overall GHG emissions of 69.63 Mt $CO_{2(e)}$ in 2005, this sector should be allocated the same percentage of the KL_{2005}, which equated

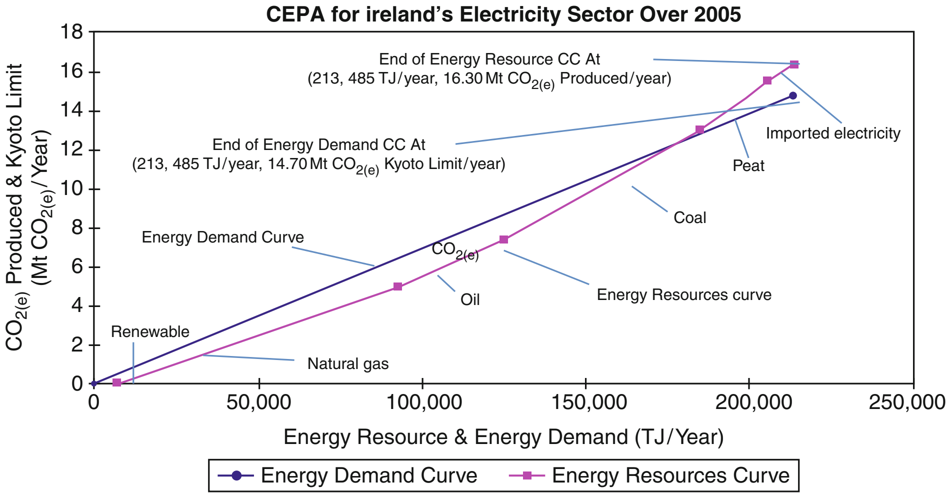

Fig. 21.29

CEPA applied to Ireland's electricity sector over 2005: before shifting of energy resource CC [38]

to 14.70 Mt $CO_{2(e)}$. This value is the vertical ordinate for the top end of the energy demand curve as shown in *Figs. 21.29* and *21.30*.

The energy demand composite curve is also constructed using the same method as the energy resource composite curve. It is assumed that the emissions from various demand sectors is proportional to the electricity usage and therefore will produce a straight line from the origin to the end of the demand composite curve. The horizontal ordinate for the top end of both the energy demand curve and energy resource composite curve should share the same value because the demand (or consumption) should match the resource (or supply) in any given year. The slope of the demand line is known as the grid emissions factor (GEF), which is simply the average emission factor for the entire system. In this case, the EF for the energy demand curve is 69.0 $t\frac{CO_{2(e)}}{TJ}$.

In *Fig. 21.29*, it is easy to find that the top end of resource curve is above the top end of energy demand curve, which shows the AER mix led to more emissions than the permitted KL of the electricity sector. Thus, the energy resource composite curve needs to be shifted horizontally to the right to get rid of the excess emissions. *Figure 21.30* shows a shifted energy resource composite curve that meets the Kyoto limit for the sector. The energy resource CC is shifted horizontally to the right until it intersects with the top end of energy demand CC and this is the CO_2 emissions pinch point. At this pinch point, the energy resources not only provide a total amount of 213,485 TJ energy per year (meeting the annual energy demand), but also release 14.70 Mt $CO_{2(e)}$ emissions (meeting the Kyoto limit of emission). In this way, the amount that the resource CC has been shifted then becomes the minimal amount of renewable energy that needs to be added in order to meet the emission target. The overhang of the resource CC to the right of the pinch point represents the amount and type of energy resources that need to be substituted by renewable energy. In this case, the renewable energy portion of the energy resource

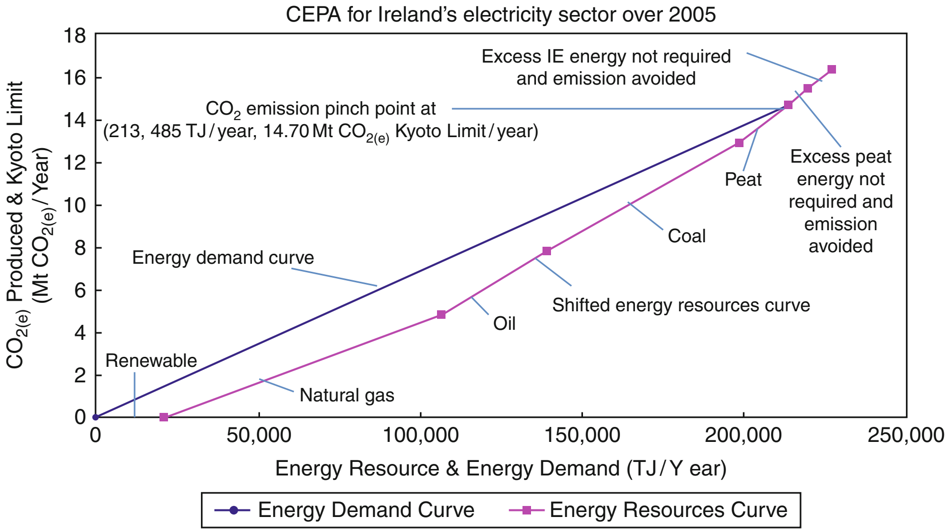

Fig. 21.30

CEPA applied to Ireland's electricity sector over 2005: after shifting of energy resource CC [38]

CC increases, the portion of imported electricity is totally substituted, and the portion of electricity from peat generation decreases as illustrated in *Fig. 21.30*. By increasing the energy resources with low emission factors and decreasing energy resources with high emission factors, the shifting procedure achieved the desired objective, that is, the emissions produced by the resources equal to the Kyoto Limit of the demand. Meanwhile, the other objective of using the minimum amount of renewable energies due to their disadvantages is also achieved by this horizontal shift procedure. Each of the line segments of the shifted energy resource CC is measured off in order to get the optimal energy resource (OER) mix in 2005, which is also the optimal energy resource allocation scheme of the sector. The corresponding emissions produced by each of these optimal amounts are also measured. All of the measured data are listed in *Table 21.7*.

Further adaptations to CEPA. Crilly and Zhelev made a forecasting adaptation to the CEPA methodology, which is briefly introduced here. If the optimal energy resources (OER) mix in the future can be predicted, then the sector's policy makers can use this information to guide the future development plan of the sector. For example, in the near future, Ireland will close old and inefficient power plants, and create new power generation plants. The ahead-of-time knowledge of the future OER mix will be particularly useful for the policy makers to decide which form of power generation plant should be constructed. As long as the future actual energy resources (AER) mix is available, the future OER mix can be obtained using the same CEPA procedure described in the proceeding section. The future AER mix can be projected based on the energy model linked with macroeconomic model together with many key forecast parameters, such as GDP growth, population growth, fuel prices, etc. In 2006, Sustainable Energy Authority of Ireland (SEAI), Ireland's national energy authority, published the projected AER mix for

the electricity sector in 2010, which is shown in Table 21.7. Crilly and Zhelev used that information to forecast the OER mix that the energy sector in 2010 should have. Their forecast is also listed in Table 21.7. Analyzing those data, the OER mix in 2010 will need to have the input of RESs rising from 7.2% of the AER mix to 8.2%. This important and invaluable information will give the relevant policy makers and stakeholders 3 years time in advance to make up for this forecasted shortfall of renewable energies in 2010 for the analysis made in 2007.

Future Trends

Heat integration is one branch of process integration technologies. In the authors' view, there are several directions that can be considered as potentially promising for the future of process integration.

Process integration, especially the newer development, has not been used as widely as it could be. It is likely to see a wider range of application in process integration. Still, there is much work to be carried out in the research of integrating heat-integrated network with separation systems and reactor designs, and the consideration of operational issues as well. Heat integration is closely related to mass integration by nature. Although extension of pinch analysis to mass integration field, such as water pinch and hydrogen pinch, has already been applied to industries successfully, systematic methods in this area are still in development. Utilizing advanced optimization techniques to solve process integration problems are very promising.

With the advancement of computer technology, a new generation of more powerful software tools for process integration may emerge. Comparing to the process simulation software, which is relatively mature, the process integration software is at its infancy. Process integration problems are generally complex tasks at considerable scales and involve comprehensive interactions. The development of powerful commercial software for process integration is instrumental for its wider application.

Climate change has recently become a major focus of industry and government. Pinch analysis has been extended to solve emissions and energy footprint problems to meet the environmental goals with technical and economic constraints simultaneously. Several methodological (graphical and numerical) approaches have been developed to handle problems such as energy allocation, segregated targeting, and retrofit planning. Meanwhile, similar approaches for considering energy, land, and water footprint issues in energy and biofuel systems have been developed. Regarding the increasing concerns on climate change, more methodologies and applications are expected in this area.

Conclusion

Heat integration is a family of methodologies that can be used to improve energy efficiency, reduce energy consumption, and minimize GHG emissions. Pinch analysis can be considered

as the foundation of heat integration. It can identify the maximal heat recovery and minimal external utility needs for the system before any detailed design. As a powerful tool, pinch analysis extends its application to many other fields, such as waste reduction, wastewater treatment, refinery hydrogen management, emission targeting, etc.

In spite of the total annualized cost, the HEN design must always consider the operability and controllability issues as well. During operations, various disturbances of temperatures and heat capacity flow rates always present. The disturbance propagation and control (DP&C) model embedded HEN design approach can estimate the disturbance propagation and reject the severe disturbances through bypass design. This method can generate an optimal design solution satisfying both the economic and control objectives, thereby ensuring the achievement of high energy efficiency and low emissions.

The novel carbon emissions pinch analysis (CEPA) methodology, developed based on traditional pinch analysis, can identify the minimal quantity of low-carbon emission energy resources needed to meet both the emission limit and energy requirement, and the optimal energy allocation scheme, for a regional or national energy sector. It can provide invaluable information for the decision makers and stakeholders.

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